agronomy

MDPI

Review

Algal-Mediated Nanoparticles, Phycochar, and Biofertilizers for Mitigating Abiotic Stresses in Plants: A Review

Zainul Abideen [1], Huma Waqif [2], Neelma Munir [2,*], Ali El-Keblawy [3], Maria Hasnain [2], Emanuele Radicetti [4,*], Roberto Mancinelli [5], Brent L. Nielsen [6] and Ghulam Haider [7,*]

1 Dr. Muhammed Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi 75207, Pakistan; zuabideen@uok.edu.pk
2 Department of Biotechnology, Lahore College for Women University, Lahore 35200, Pakistan; humarana76@gmail.com (H.W.); maria.hasnain255@gmail.com (M.H.)
3 Department of Applied Biology, College of Sciences, University of Sharjah, Sharjah P.O. Box 27272, United Arab Emirates; akeblawy@sharjah.ac.ae
4 Department of Chemical, Pharmaceutical and Agricultural Sciences (DOCPAS), University of Ferrara, 44121 Ferrara, Italy
5 Department of Agricultural and Forest Sciences (DAFNE), University of Tuscia, 01100 Viterbo, Italy; mancinel@unitus.it
6 Department of Microbiology and Molecular Biology, Brigham Young University, Provo, UT 84602, USA; brentnielsen@byu.edu
7 Department of Plant Biotechnology, Atta-ur-Rahman School of Applied Biosciences, National University of Sciences and Technology, Islamabad 44000, Pakistan
* Correspondence: neelma.munir@lcwu.edu.pk (N.M.); emanuele.radicetti@unife.it (E.R.); ghulam.haider@asab.nust.edu.pk (G.H.)

Citation: Abideen, Z.; Waqif, H.; Munir, N.; El-Keblawy, A.; Hasnain, M.; Radicetti, E.; Mancinelli, R.; Nielsen, B.L.; Haider, G. Algal-Mediated Nanoparticles, Phycochar, and Biofertilizers for Mitigating Abiotic Stresses in Plants: A Review. *Agronomy* **2022**, *12*, 1788. https://doi.org/10.3390/agronomy12081788

Academic Editor: Baskaran Stephen Inbaraj

Received: 8 June 2022
Accepted: 22 July 2022
Published: 29 July 2022

Abstract: The excessive use of agrochemicals to ensure food security under the conditions of a growing population, global climate change, weather extremes, droughts, wasteful use of freshwater resources, and land degradation has created severe challenges for sustainable crop production. Since the frequent and abrupt environmental changes are outcompeting the existing agricultural technologies of crop production systems to meet food security, the development and use of modern technologies and nature-based solutions are urgently needed. Nanotechnology has shown potential for revolutionizing agri-production and agri-business in terms of nanofertilizers and nanoparticles for crop protection. Furthermore, in the recent past, biochar has been identified as a negative emission technology for carbon sequestration and soil fertility improvement. However, supply chain issues for biochar, due to feedstock availability, challenges its worldwide use and acceptability. Meanwhile progress in algae research has indicated that, algae can be utilized for various agro-ecosystem services. Algae are considered an efficient biological species for producing biomass and phytochemicals because of their high photosynthetic efficiency and growth rate compared to terrestrial plants. In this context, various options for using algae as a nature-based solution have been investigated in this review; for instance, the possibilities of producing bulk algal biomass and algal-based biofertilizers and their role in nutrient availability and abiotic stress resistance in plants. The potential of algae for biochar production (hereafter "phycochar" because of algal feedstock), its elemental composition, and role in bioremediation is discussed. The potential role of agal nanoparticles' in mitigating abiotic stress in crop plants was thoroughly investigated. This review has effectively investigated the existing literature and improved our understanding that, algae-based agro-solutions have huge potential for mitigating abiotic stresses and improving overall agricultural sustainability. However, a few challenges, such as microalgae production on a large scale and the green synthesis of nanoparticle methodologies, still need further mechanistic investigation.

Keywords: algal biomass; hydrothermal carbonization; phycofertilizer; phycochar; pyrolysis; torrefaction

1. Introduction

Surface temperature rise is increasing gradually and is expected to reach 3.2 °C by the end of the century. Global warming affects the world by influencing food production systems, leading to hunger, malnutrition, and increased poverty that can damage all life forms [1]. Climate change has become a reality, and its effects on water, agriculture, health, biodiversity, forests, and socioeconomic sectors can be seen worldwide. In comparison to developed nations, developing and less developed countries are likely to suffer more due to climate change [2]. Extreme weather events like prolonged drought spells or erratic rainfalls leading to flooding are likely to become more common in the future. Over the last 20 years, the media has paid increasing attention to climate change [3,4], and concerns about global warming and climate change issues have evolved progressively.

2. Salinity, Drought, and Flooding as Abiotic Stresses

Salinity is among the most severe worldwide challenges affecting agricultural productivity. Salinity stress is caused by the osmotic effect, cytotoxicity of ions, such as Na^+ and Cl^-, and nutritional imbalance. All these effects of salinity stress inhibit plant growth and development [5]. Isayenkov [6] stated that salinity causes oxidative stress resulting from the production of reactive oxygen species (ROS). ROS are unstable oxygen-containing molecules that easily react with other molecules in a cell. A deposition of ROS in cells can damage DNA, RNA, and proteins and can cause cell death as well. Salinity stress can inhibit metabolic processes and result in early aging and cell death. Plants respond to salt stress through the closure of stomata, inhibition of cell expansion, and reduction of root surface area to reduce ion uptake [7].

During the previous century, increases in greenhouse gas emissions and temperature have led to extreme weather conditions with more frequent droughts and floods. Droughts cause severe stress on the hydrological cycle, with serious consequences on economy, society, and the environment. Extreme drought events can have a major influence on soil ecosystem functioning [8], plant morphology [9], and productivity [10]. Thus, the agriculture ecosystem is so vulnerable to drought that severe droughts can negatively impact global food security. Drought-related damages are often assessed using socioeconomic parameters such as economic and agricultural productivity loss. As a result, it is critical to employ relevant indicators to assess the effects of severe droughts on agricultural soil and to examine the long-term viability of soil ecosystems under adverse drought spells [11]. Floods are the worst type of hydro-meteorological hazard on planet Earth. Flooding is the most striking interaction between man and his environment, emphasizing both the tremendous intensity of natural occurrences and man's inability to control these [12]. Examples of severe floods include river flooding, urban drainage, coastal flooding, erosion, and ground flooding erosion. The mechanics of riverine flooding differ depending on the topography. Floods in flat regions can be shallower and slow-moving for days or even weeks. Floods can occur in minutes after heavy rain in hilly and mountainous areas. Flash floods are extremely dangerous because of their spontaneous nature, huge depths, and strong velocity. Over one-third of the globe's land area is prone to flooding, affecting around 82% of the world's population [13]. Between 1980 and 2010, about 196 million people were exposed to severe flooding in 90 countries, and 170,000 people died because of floods globally, according to The United Nations Development Programme 2004 (UNDP). Flooding is the most prevalent of all environmental hazards, claiming thousands of lives each year and affecting millions of people throughout the world [14].

High temperature, drought, salinity, and floods all pose serious challenges to food production systems and security by affecting land resources and inefficiencies in agricultural inputs. Various strategies have been developed and successfully adapted with a degree of success. However, almost all strategies have shown certain tradeoffs, ultimately challenging the sustainability of the system. Abrupt changes in climate are the main cause of abiotic stress and influence agricultural food security. Agricultural productivity and climate perturbation are associated factors and potentially cause biotic and abiotic stresses, which have adverse effects on the agriculture of a region. Abiotic stresses play a major role in plant distribution across different types of environments and maintaining the eternal stability of the ecological system is the most important worldwide ecological challenge. Over 90% of crop fields, resulting in a 70% decline in the production of major food crops, were affected due to abiotic stress. The alarming conditions have evolved because of unanticipated environmental changes, human activity, and inadequate agricultural strategies [15]. Abiotic stress conditions trigger the production of reactive oxygen species (ROS), which, if not detoxified, will certainly reduce the quality of the soil and subsequent fertility. The production of reactive oxygen species inhibits many cellular functions at various levels of metabolism, such as photosynthetic activity, biochemical processes, carbon assimilation, and membrane permeability, resulting in a decrease in crop production [16].

To reduce the negative effects of abiotic stress and improve plant stress resistance, various agronomical methods have been employed, including nanotechnology biochar amendment, and bio-fertilizer from various sources have also been considered for mitigating abiotic stresses [17–19]. Nanotechnology attracted interest, particularly in developing effective and environmentally friendly procedures, for resolving the problems associated with abiotic stresses [20,21]. NPs are acquiring great importance in the field of biological research due to their unique physio-chemical features, such as having high stability within cells, an extremely small size (1–100 nm), increased surface area, and reactivity. The application of NPs improves plant stress resistance by increasing their radical detoxifying capacity and antioxidant enzymatic activities, which considerably help in the regulation of plant physio-biochemical and metabolic processes [22,23].

Plant adaptation to the negative impacts of abiotic stress is critical for maintaining sustainable crop growth and output. Different soil management strategies that improve soil fertility and water availability might be employed as abiotic mitigation tools in both irrigated and non-irrigated areas. The use of biochar as a soil supplement is an ancient idea, but it has recently gained interest due to reducing climate change issues and improving soil fertility and water usage efficiency and crop yield [24]. Biochar amendment in agriculture has recently been acknowledged as a sustainable technique due to its advantages for soil sustainability and crop yield. Biochar mitigates the negative effects of drought stress on plant physiology, growth, and yield by modulating soil and plant nutrient status and plant photosynthesis [25,26]. In addition, the application of bio fertilization is another sustainable agriculture strategy that involves utilizing biofertilizers to increase soil nutrient content, resulting in increased photosynthesis and biomass production. Different new organisms, including algae, have potential agricultural uses, such as providing biofertilizers and being soil conditioning agents for improving soil fertility and plant production [27].

Microalgae can produce plant growth hormones, polysaccharides, antibacterial compounds, and other metabolites to improve soil fertility and quality (e.g., *Spirulina* sp., *Chlorella* sp., Cyanobacteria (blue-green algae)) [28]. Cyanobacteria and green microalgae are the key organic matter sources in the agro-ecosystem because they actively contribute to the absorption of atmospheric carbon dioxide into organic microalgae biomass through photosynthesis [29]. Microalgae are considered an organic fertilizer because they may reduce nutrient losses through a gradual release of P, N, and K, yet they are more temperature and soil moisture tolerant than organic fertilizers [30], such as *Dunaliella* spp. and *Phaeodactylum* spp. Their potential to minimize salt stress during the seed germination phase of bell pepper (*Capsicum annuum* L.) has been demonstrated in research studies [31]. Extracts of microalgae and different algal species have been demonstrated to enhance wheat tolerance to salt, as well as improve the antioxidant capacity and protein levels in whole grains [32].

Algae are autotrophic photosynthetic organisms that can colonize even the most diverse environments. As algae are subjected to frequent and mostly abrupt fluctuations in intensities of light, salt stress, temperature, and food availability, they have acquired the ability to produce a diverse range of secondary metabolites. These are mostly required to cope with and adapt to abiotic stress. In addition to this functional variety, which includes distinct adaptations to different habitats and pressures, the algal biochemical profile is also highly diverse due to a wide taxonomic range and evolutionary variation. Because of its widespread distribution, quick growth, and high CO_2 fixation efficiency, algal biomasses are seen as a viable substrate. A possible improvement in biomass-to-biochar conversion by thermochemical processes such as pyrolysis, hydrothermal carbonization, or torrefaction would be beneficial for further exploiting algal biomass from the perspective of biorefinery [33].

3. Sustainable Solutions to Improve Soil Conditions and Plant Health

Meeting the growing demand for agricultural products, as well as the innovations toward quality and higher yields, can be made possible by incorporating innovative agricultural technologies [34]. For example, applying microbial inoculants to plants and soils can regulate nutrient absorption and increase crop productivity. In addition, microorganisms have been utilized as biocontrol agents and for relieving plant abiotic stress caused by drought, soil pollutants, and salt [35]. Diverse microbial consortia can induce favorable conditions for the growth of beneficial microbes as well as plants. Rich microbial flora can improve important soil characteristics such as soil structure, aggregation, compaction, pore spacing, and water penetration [36]. In addition, algae are a diverse group of mostly photosynthetic microorganisms that comprise both prokaryotic (cyanobacteria) and eukaryotic (green algae, euglenoids, and diatoms) species [37]. Algae can significantly raise soil fertility, which assists with plant development and protection by increasing nutrient availability [38], and provides an effective alternative to chemical fertilizers and pesticides in agricultural contexts, as well as producing bioactive chemicals such as phytohormones [39], developing root networking [40], and defending crops from plant pathogens and pests [40]. Microalgae fix CO_2 through photosynthesis for carbon sequestration, and some produce exopolysaccharides (EPS) that improve soil structure [41]. Because of their ability to fix atmospheric nitrogen (N_2) and, more importantly, their ability to solubilize the immobilized pools of phosphorus (P), cyanobacteria (blue-green algae) are referred to as biofertilizers [42]. Furthermore, microalgae may be grown on nutrient-rich effluents, helping to accumulate excessive nutrients that can be recycled for plant growth at a lower rate than chemical fertilizers [43].

Algal biomasses are important because of their high fiber content, which helps to retain soil moisture and thereby improves the availability of nutrients and trace elements. Photosynthesis performed by algal cells protects the plant root system in terms of respiration against anaerobiosis. In plant growing systems, algae produce plant growth regulators such as cytokinin, auxin, gibberellin, micro and macro elements, amino acids, vitamins, and abscisic acid, which have a major role in crop development and higher crop yield [44].

In addition, nanotechnology, which uses matter on an atomic and molecular scale, can alleviate a wide range of challenges in the agriculture industry. Nanotechnology's promising applications in agriculture include nutrient delivery and the detection of pathogens, toxins, and pesticides. The proper applications of nanotechnology in plant disease and growth management can help tackle problems linked to the usage of fertilizers and pesticides and their impacts. Nanotechnology can also provide sensors to monitor physical, chemical, or biological processes, making agriculture more sustainable. The sensors can control pathogens for improving food safety and reducing wasted food. This technology can also provide materials for the timely and targeted delivery of chemical fertilizers and pesticides [45].

4. Use of Algal Biomass

Nutrient-rich water in ponds, rivers, lakes, and bays causes algal blooms–a phenomenon called eutrophication. This phenomenon can happen equally in fresh and saltwater, typically because of high concentrations of nitrogen and phosphorus. These nutrients generally runoff from agricultural drainage, sewage, and animal wastes. Algal blooms mostly constitute biotoxins, which are distinguished by a unique watercolor due to the presence of algal pigments [46]. Yu et al. [47] reported that the use of microalgae as a feedstock to produce biochar is more promising than macroalgae; microalgae grow faster and are more easily cultivated and harvested than macroalgae. Currently, an important trend exists for integrating algae cultivation with wastewater remediation. This process has a dual benefit: wastewater remediation and biomass production. Microalgae have the potential for the phytoremediation of wastewater that is rich in nutrients, especially phosphorus and nitrogen. Algal remediation or phycoremediation could be applied during the secondary-treatment processing of wastewater to biologically oxidize organic contents and accumulate nutrients [48]. Such a process is more efficient and safer compared to other physico-chemical treatments. Biochar is a carbon-rich material produced by the pyrolysis of organic biomass at 250 °C to 1000 °C in the absence or limited supply of oxygen. Here the term phycochar has been used, which is associated with 'Phycos', meaning algae, and the biochar produced by tacking algae as feedstock. Algal biomass produced in the phycoremediation process could be converted to organic manure, bio-fertilizers, or biodiesel. Furthermore, it has been reported that using microalgae as biofertilizers is a cheaper and more renewable resource that contains the essential nutrients needed for plant growth [49]. Liquid and slow-release algal bio-fertilizers were tested and showed efficiency in agriculture. In addition, living N-fixing cyanobacteria (blue-green algae) have shown efficiency in enhancing soil fertility and crop productivity [50].

5. Production of Phycofertilizer from Algae

Biofertilizers are a mixture of live or dormant microorganisms that can fix atmospheric nitrogen, decompose organic material, and increase the solubility of soil minerals. Biofertilizers increase the abundance of beneficial microorganisms, enhancing plant growth [51]. Recently described algal biofertilizers contain high essential micro and macronutrients, growth enhancers, vitamins, and growth-promoting hormones, which have demonstrated promising outcomes. Algal biomass has a longer life span (post drying), is less thermosensitive, and is more resilient for transport and storage. Therefore, algal biomass can serve as a source of nutrition and as a carrier material to form biofertilizers [52]. Some studies have reported that algae and several bacteria produce exopolysaccharides that could be used as a C-source. Several bacteria produce residual fluids and exopolysaccharides that can also serve as carbon sources for rhizosphere bacteria [53]. The decomposition of applied dry cyanobacteria and diatoms in the plant's rhizosphere produces cellular extracts that enhance the generation of siderophores from some bacteria [54]. Red and brown algae were exploited as natural manure in farmlands near the sea; these algae are generally rich in K but poor in N and P. Algal species produce a wide range of secondary metabolites utilized in agriculture as biofertilizers and biopesticides. It has been stated that weed control could be accomplished either by the direct spray of algal liquid pesticides or by solid algae plowed into the soil [55]. In addition, liquid algal biofertilizer is the most applied method used in the agricultural field. These liquid fertilizers primarily have high trace elements and growth regulatory compounds, which positively impact plant growth and development (particularly cytokinins) (Figure 1). Algal extracts possess several essential nutrients, including Zn, K, Mg, Ca, P, S, K, Zn, Mo, Cu, Co, and Fe, and several growth regulators, vitamins, and polyamines that increase nutritional status, vegetative development, yield, and fruit quality in various orchards and vineyards. Several phytohormones, phenolic compounds, polysaccharides, terpenoids, free fatty acids, and alpha and beta carotenoids are produced by microalgae and cyanobacteria. These compounds are a source of essential nutrients and have biological activity, significantly improving crop yields [56]. (Table 1).

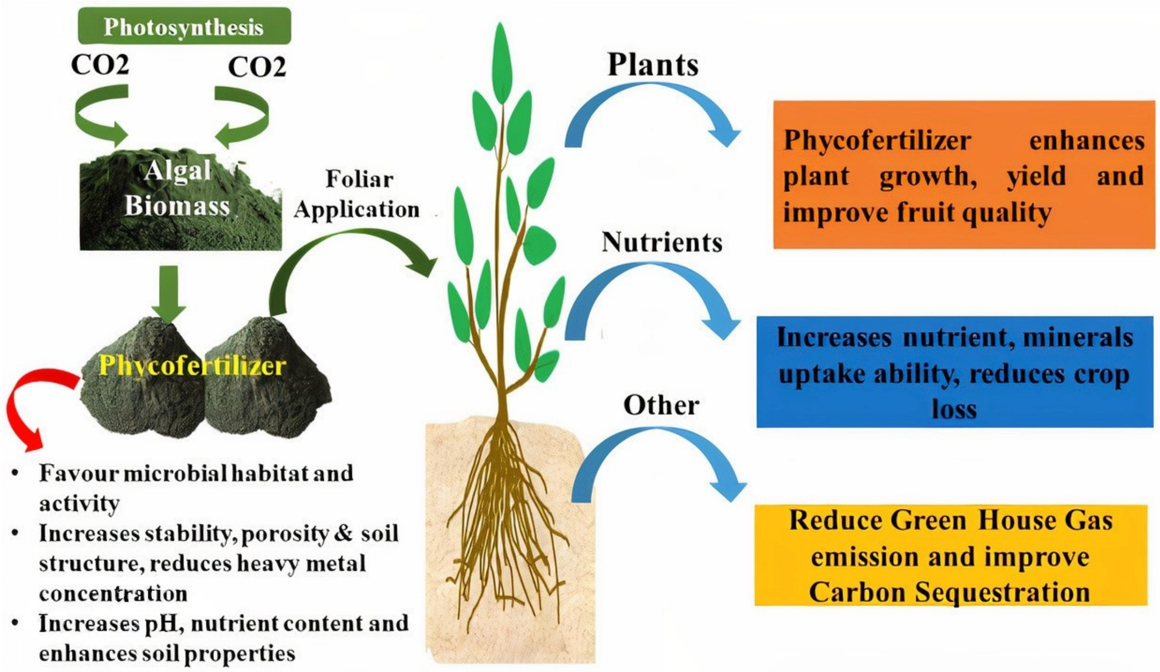

Figure 1. Applications of phycofertilizers in agriculture.

Table 1. Algal metabolite impacts on agriculture.

Algal Species	Metabolites	Biological Activities	Tested Crop	Observed Improvement	References
Chlorella vulgaris	Polyphenols flavonoids; phenolic acids	Anti-fungal, anti-oxidant, and anti-microbial	Maize Crop	Plant protection against pathogens, viuses, or other biotic and abiotic stress conditions. Enhances germination rate and crop yield	[57–59]
Nostoc sp.	Structural polysaccharides, extra cellular Polysaccharides, and energy-storage poly-saccharides	Anti-bacterial, anti-cancer, anti-oxidant, and anti-coagulant	Pepper	Improves the quality of soil, plant growth stimulation, and plants protection against abiotic and biotic stresses	[60,61]
Dunaliella salina	Alpha-Beta carotene lycopene, astaxanthin, and zeaxanthin	Anticancer, anti-inflammatory, and antioxidant	Wheat Crop	Soil fertilization and bioremediation, plant crop protection against bacteria, viruses, and other abiotic and biotic stress conditions. Plant's fortification, improved germination rate, and seedling growth	[62,63]
Anabaena sp.	Fatty acids, saturated and unsaturated	Antifungal, antiviral, and antioxidant	Rice Crop	Plant's protection against pathogens or other biotic and abiotic stress conditions, increase in germination rate, the height of the plant, increased soil moisture and porosity	[61,62,64,65]

Table 1. *Cont.*

Algal Species	Metabolites	Biological Activities	Tested Crop	Observed Improvement	References
Arthrospira platensis	Auxins, cytokinins, abscisic acid, ethylene, and gibberellins	Chemical messengers	Lettuce Crop	Plant growth stimulation. Regulation of cellular activities in crops plant's response to stress conditions enhances seedling growth	[66,67]
Spirulina platensis	Saturated & unsaturated fatty acids	Antibiotic, antifungal, antioxidant, and antiviral	Maize Crop	Protection against pathogens or other biotic and abiotic stress conditions increased plant yield and shoot length, and no of plant leaves	[68,69]
Oscillatoria sp.	Hemiterpenes, Mono, di tri & poly terpenes	Antibacterial, anticarcinogenic, and antioxidant	Wheat Crop	Plant's protection against bacteria, and viruses. Stimulation of primary growth of plants, increase in activity of plant's defense enzymes, alleviation of drought stress	[70,71]

6. Role of Phycofertilizer in Stress Resistance

Salinity stress is an important and growing challenge, especially in arid and semi-arid regions of the world. The agricultural area impacted by severe salinity is growing due to both natural phenomena such as global warming and poor agricultural practices on a global scale. Salinity threatens plant growth in several ways, including ionic toxicity, osmotic stress, oxidative stress, and nutritional disruption. For example, oxidative stress has negative effects on several physiological and metabolic systems in plants. Several techniques have been adopted to minimize the effects of salt on plants, including using organic fertilizers, biofertilizers, and growth regulators. Cyanobacteria are considered as a good biofertilizer [72]. These blue-green algae can survive and grow in various soil conditions, including high pH and salt, and are utilized to reclaim calcareous and saline soils. Alam et al. [73] indicated that cyanobacteria affect plant nutrient supplies in various ways. They produce adhesive substances that increase soil aeration, produce growth-promoting compounds, minimize the effects of salt stress, and raise both water content and soil biomass during decomposition. In addition, Cyanobacteria increase nitrogen content by nitrogen fixation and soil phosphate by releasing organic acids into the soils. Several studies have reported the positive benefits of cyanobacterial inoculation to mitigate salinity stress in plants [74].

Salinity can have an impact on all stages of plant development. One of the most critical and sensitive stages is seed germination. Soil salinity can cause osmotic stress in developing seeds by reducing water uptake [75]. According to Aljasmi et al. [76], seeds germinated in saline solution develop secondary dormancy that reduces germination percentage and speed. Salinity increases the accumulation of Na^+, Cl^-, and proline content in germinated seeds while decreasing the accumulation of Ca^+ and K^+ [77]. Different cyanobacteria produce various types of growth-regulating substances that enhance seed germination in saline soils. For example, Rodriguez et al. [78] reported that the cyanobacterium *Scytonema hofmanni* produced gibberellic acid that enhanced rice seed germination and seedling growth in a saline medium. In addition, the application of cyanobacteria extracts significantly increased the average germination of *Lupinus termis* seeds treated with different growth regulators, such as indole acetic acid, gibberellic acid, and cytokinins seeds, compared to controls. In addition, rice seeds treated with four species of Anabaena, a genus of cyanobacteria, significantly increased the rice seeds' final germination and germination rate [79]. Refining the fertility of saline soils is critical from an agricultural perspective. Saline soils contain high levels of soluble salts in the root zone that negatively impact crop development and output. The most common salt present in saline soils is sodium chloride. Algal biofertilizers play an important role in the reclamation of saline soils. Several species of cyanobacteria, such as *Plectonema, Nostoc*, *Calothrix*, and *Scytonema*, can tolerate high salinity and alkalinity in soils [80]. Cyanobacteria tolerate high levels of salinity through several mechanisms. They accumulate osmolytes, such as sugars, proline, polyamines, and glycine betaine, to regulate their negative water potential. Cyanobacteria also maintain low salinity levels in the cells either through salt compartimization in cell vacuoles, specific tissues, or organs by excluding most Na^+ and Cl^- into the soil [81]. Furthermore, cyanobacteria produce hormones, like auxin and cytokinin, that help the plant survive stress conditions. Moreover, they release other metabolic compounds like indole acetic acid, auxins, and iron-chelators that regulate several biochemical and physiological processes [82]. It has been reported that the application of cyanobacteria to agricultural fields provides renewable sources of carbon and nitrogen. *Heterocystous Cyanophyta* have long been utilized as a nitrogen source in rice fields in Asia because they can successfully fix nitrogen for crop plants. It has been shown that rice plants utilize roughly 40% of the nitrogen fixed by the *Cyanophyta*. The importance and use of *Cyanophyta* have also increased in other developing nations, where economic restrictions prevent using more traditional chemical fertilizers. The use of organic fertilizers such as *Cyanophyta* also helps decrease the use of synthetic fertilizers and pesticides, which negatively impact soil productivity and environmental quality in the long term [83].

7. Role of Phycofertilizer in Drought Resistance

Drought is important environmental stress that challenges agricultural production and food security. Fresh water will continue to be a scarce commodity, especially with ongoing global climate change. Soil water potential resulting from soil salinity and drought can influence germination and all stages of growth and development in plants. Physiological, biochemical, and molecular responses in agricultural crop plants aid them in adapting to such harsh environmental conditions [84]. Drought influences plant growth, structure, membrane integrity, tissue osmotic potential, pigment content, antioxidant defense systems, and photosynthetic activity [85,86]. In response to drought stress, plants increase their root-to-shoot ratio and regulate many physiological processes like nitrogen and carbon metabolism, transpiration, and the production of secondary metabolites [87]. Drought stimulates ROS overproduction, such as singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radicals, which cause oxidative damage in plants [88,89]. Both enzymatic and non-enzymatic antioxidant systems protect cells from oxidative stress and keep the levels of ROS within an acceptable range. Bioactive chemicals produced from marine algae have recently been used as biofertilizers in agricultural and horticultural crops to enhance output and quality while minimizing drought, salinity, and mineral deficiency stresses. In addition, seaweeds are a good source of bioactive growth-promoting components, namely fatty acids, amino acids, vitamins, minerals, and growth hormones [90,91]. They have also been found to boost antioxidant defense, increase plant growth and biomass production, and contribute to drought tolerance. For example, microalgal extracts enhanced drought tolerance in broccoli seedlings; therefore, microalgae may be a viable alternative for crop enhancement and protection in agriculture [92]. Similarly, Duo et al. [93] indicated that the inoculation of turf grass with the microbes *Bacilluscereus, Lysinibacillus* sp., and *Rhodotorula glutinis* alleviated the adverse effects of drought. Nano-compost and microbial inoculation both increased shoot and root biomass by 209% and 215%, respectively, under severe drought stress, compared to controls.

Plants respond to microalgal treatment in several ways, including enhanced growth and productivity, better nutrient absorption, stress tolerance induction, and postharvest quality preservation. Applications of microalgal extracts can also help mitigate the detrimental effects of abiotic stresses such as drought and salt [93]. Microalgae extracts reduced salt and drought stress impacts on wheat, tomato, and guar. For example, foliar application of the microalgae *Chlorella vulgaris* significantly increased antioxidants, including total flavonoid and phenolic content, which reduced ROS levels in broccoli plants subjected to drought stress. This antioxidant scavenging activity of ROS reduced membrane damage and improved chlorophyll and carotenoid content and nutrition uptake, resulting in adaptation to drought stress [94].

8. Production of Phycochar from Algae

Organic biomass, such as crop residues, forest residue, animal manure, algal biomass, etc., are significant sources of biochar production [34]. Biochar is a porous material produced from organic materials in the pyrolysis process that happens in an oxygen-depleted environment at various temperatures. Many approaches are used to produce algal biochar (herein phycochar) from algae, as shown in Table 2.

Table 2. Comparison of biochar yield from algae using different thermochemical methods.

Algae	Biochar Production	Pyrolysis (°C)	Biochar Yield (%)	Application	References
Chlorella vulgaris	Fast pyrolysis	500	30	Biofertilizer	[95]
Spirogyra sp.	Slow pyrolysis	900	18.6	Fuel & soil amendment	[96]
Cladophora sp.	Slow pyrolysis	900	32	Fuel & soil amendment	[97]
Oedogonium intermedium	Slow pyrolysis	450	29	Biofertilizer	[98]
Chlamydomans sp.	Torrefaction	200 to 300	93.8	Fuel	[99]
Scenedesmus sp.	Pyrolysis	600	36	Soil amendment	[100]
Chlorella vulgaris	Wet Torrefaction	180	53	Fuel	[101]
Chlorella vulgaris	Fast pyrolysis	500	26	Soil fertility	[102]
Laminaria japonica Brown Macroalgae	Slow Pyrolysis	200–800	78	Metal removal efficiency, Soil amendment	[34]
Cladophora glomerata Green macroalgae	Fixed-bed pyrolysis	400–600	43.98	Fuel, Biofertilizer	[103]
Chlamydomans reinhardtti	Slow pyrolysis	350	44	Nitrogen releasing fertilizer	[104]

Gasification, pyrolysis, and liquefaction are three types of thermochemical conversion of organic materials into biochars, as shown in (Figure 2). Thermochemical processes such as pyrolysis, hydrothermal carbonization, and torrefaction are generally used for converting algae into biochar [34]. Hydrothermal carbonization is another process to produce hydrochar from algal biomass [105]. The pyrolysis method is commonly chosen for biochar production because it is simple and cheap and provides both the quality and type of biomass feedstock for wider usage. There are various forms of pyrolysis to make biochar, including traditional slow pyrolysis, fast pyrolysis, and the most recently developed microwave-assisted pyrolysis. Each pyrolysis process produces solid, liquid, and gaseous bioproducts in response to different parameters like temperature, time, etc. Slow pyrolysis yields only biochar, whereas rapid pyrolysis leads to bio-oil production as a byproduct in addition to the biochar [106]. In pyrolysis, the temperature generally employed for biochar production is 300–700 °C, and the process takes place in an oxygen-depleted environment. Several variables, most notably heating rate and temperature, influence the pyrolysis results [107]. Biochar yield increases when pyrolysis temperature is reduced, and reaction time is increased with a lower heating rate. Furthermore, the particle size and moisture content significantly influence the biochar production rate produced during the pyrolysis process [108]. This carbonaceous material has been used in agriculture for improving soil quality, nutrients, and water-use efficiency. It increases water holding capacity and enhances nutrient content, especially in desert soils [109]. Elemental composition analysis has indicated that algal biochars provide a full suite of macro and micronutrients required for plant development. The relatively high amounts of N, P, and K imply that algal biochar can be used as a fertilizer without adding supplementary components. Various elements and ash are present in algal biomass. However, some hazardous trace metals are present in the biochars. Therefore, some nations have set minimum amounts of biosolids to be absorbed into agricultural soils. Interestingly, biochar is currently used on a wide scale to remove contaminants from water and soils by adsorption [104,110].

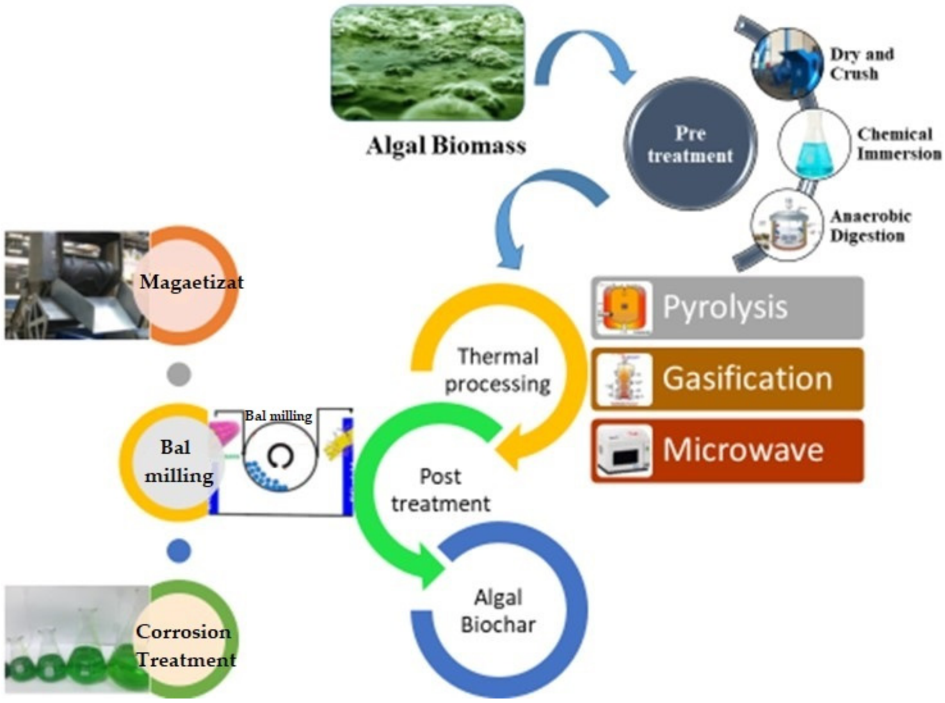

Figure 2. Production of phycochar from algal biomass by different methods.

Table 3. Chemical analysis of algal biochar. Note that all the values are in percent (%).

Algae	Carbon	Nitrogen	Oxygen	Hydrogen	Ash	Reference
C. reinhardtii	40	5	10	1.5	45	[34]
Scenedesmus sp.	53	6.5	40	8.5	44	[111]
Almeriansis sp.	73	5	0.8	9	36	[112]
L. saccharina	74	3	14	8	-	[113]
Cladophora sp.	12	1.3	11	0.7	75	[114]
Arthrospira sp.	48	11	-	-	-	[112]
Gracilaria sp.	31	3	16	2.2	43	[34]
Spirulina sp.	46	10	34	7	7	[34]
Lyngbya sp.	70	7	22	2.5	-	[115]
D. tenuissima	20	1	22	3	-	[50]
Kappaphycus sp.	31	0.7	23	2	-	[116]
Enteromorpha sp.	16	2	-	2	-	[111]
Desmodesmus sp.	51	7	14	3	37	[115]
Oedogonium sp.	12	1	6	1	-	[116]
Spirulina algae	69	7	15	9	-	[117]
Ulva	73	7	11	8	-	[118]
Cyanobacteria sp.	76	6.3	7.39	9	-	[119]
Chlorella	51	10	30	8	-	[113]
Ulva fasciata	26	3	-	6	15.99	[120]
Caulerpa taxifolia	25	2.5	-	1.19	-	[121]

Biochar is marketed as a carbon-negative technology [122]. It is a more stable type of carbon than organic carbon and is capable of staying in the soil for decades. Therefore, biochar can significantly assist with carbon storage in the atmosphere. The stability of biochar with a high carbon content can play a major role in greenhouse gas mitigation. It has been considered good for carbon sequestration into the soil [123]. Almost 48% of the biomass from carbon can be retained in stable biochar by the pyrolysis process [123], as described in (Table 3). According to Ghani et al. [123], biomass subjected to a slow pyrolysis method with a vapor residence time of minutes to hours retains a high carbon content in the biochar. For high-yield char generation, vapors are limited and intensively interact with the solid phase. According to Suganya et al. [124], slow pyrolysis is generally conducted at low heating rates of 0.1–1.0 K/s and a residence time of 450–550 s. Kambo et al. [125] used a slow pyrolysis approach to produce phycochar from three kinds of freshwater algae, including Spirogyra, Spirulina, and Cladophora. Pyrolysis can produce biofuel in gas, bio-oil, and biochar. Phycochar might be used to decrease soil acidity while increasing inorganic nutrients. These algae have a low oil content compared to other kinds of algae used for biodiesel manufacturing. Because of its molecular structure, it is chemically and physiologically stable, which means it may survive in the soil for 100 or even 1000 years. Decomposition of the biochar occurs at low temperatures, and carbon-rich biochar is produced [125].

9. Biochar Alleviates the Negative Effects of Drought Stress

Drought, which is a phenomenon that usually happens due to a water deficit resulting from low rainfall, has harmful effects on plant physiological and biochemical processes, reducing crop growth and productivity and affecting global food security. Drought affects cellular water potential, reducing water turgidity and normal cellular functions. Several studies have reported a reduction in photosynthesis, plant growth, and crop productivity [126] under drought conditions. The drought effect is obvious at different stages of the plant life cycle, i.e., seed germination, seedling, vegetative, and reproductive stages. However, several studies reported the ameliorating effects of biochar on plants subjected to drought [123,127,128]. Ullah et al. [129] proposed that biochar properties, such as higher pH, ash, nitrogen, and extractable inorganic nutrients, enhance plant growth under drought stress. In addition, Akhtar et al. [130] indicated that the ability of biochar to retain carbon in the soil reduces the harmful effect of drought stress on plant growth. Furthermore, biochar improves soil physicochemical and biological properties, improving overall water-holding capacity that mitigates the effect of drought on plants [131]. The use of biochar improved the growth and biomass of drought-stressed plants [132]. For example, under drought stress, biochar increased the leaf surface area and the growth of okra plants. Furthermore, biochar treatment improved several physiological attributes, including relative water content, transpiration rate, leaf osmotic potential, and photosynthesis efficiency, resulting in significant increases in several growth parameters of maize crops grown under drought stress conditions [133]. Similarly, biochar increased the ability of soil to retain water under water deficit conditions in semi-arid Mediterranean environments, enhancing the biomass of field-grown wheat [134]. Furthermore, drought has significantly reduced all growth and yield parameters of wheat, yet biochar application significantly improved their water use efficiency and physiological attributes, increasing the number of fertile tillers, spike length, and number and weight of the grains [135]. However, biochar application with 2% w/w soil improved soil moisture-holding capacity but did not improve important physiological parameters of *Silybum marianum* under moderate and severe drought stress conditions [136].

Recently, algal biochar has been found to provide a suitable surface for enhancing the activity of plant-growth-promoting bacteria. The combined application of algal biochar and growth-promoting bacteria (*Serratia odorifera*) significantly increased several growth parameters in maize, including the number of leaves, leaf area, fresh and dry biomass, shoot height, and root length in soils, during low and high drought levels (75 and 50% field capacity) [132]. Biochar application improved soil biochemical properties (carbon, potassium, nitrogen mineralization, microbial activities), which resulted in a significant increase in wheat growth under drought conditions. The increase in soil carbon enhances soil microbial communities, resulting in an enhancement of soil fertility. In addition, the ameliorating effect of algal biochar under drought stress was attributed to its ability to improve soil organic matter, that in turn improves the physicochemical and biological properties of soils, including water holding capacity and nutrient availability [137].

10. Phycochar Improves Plant's Performance under Combined Drought and Heavy Metals Stress

Several studies reported a significant reduction in growth, biomass, and yield of plants subjected to the individual application of drought or heavy metals and the combined effects of the application of both [138,139]. For example, red maple seedlings that grew under drought stress and/or in soils contaminated with heavy metals (Ni, Cu, Co, and Cr) exhibited a significantly reduced total leaf area, total leaf dry weight, and stem length. The heavy metal content was significantly increased under drought stress. De Silva et al. [138] suggested that heavy metals might reduce water absorption, exaggerating the drought effect in the combined heavy metal and drought treatments. In addition, both cadmium and drought stress and their combination significantly decreased several plant growth, yield, pigment content, gas exchange parameters, and antioxidant enzyme activities, and increased oxidative stress in wheat plants. However, the application of biochar significantly decreased the cadmium concentrations of different organs of the plants. Furthermore, biochar application significantly reduced cadmium uptake and improved biochemical and physiological attributes, resulting in significant increases in growth and yield parameters, even under high drought and high cadmium treatment [140].

In another recent study, Mansoor et al. [139] indicated that the combined application of drought and heavy metal stress disturbs soil fertility and plant growth. Heavy metals pose severe biological toxic effects. Biochar, a carbon-rich source application, alleviates this stress by increasing plant growth, biomass, nutrient uptake and improves gas exchange under drought stress. The application of biochar reduces drought stress by increasing soil water holding capacity through the modification of soil physio-chemical properties that, in turn, increase water availability to plants and enhance the mineral uptake and regulation of stomatal conductance. Biochar mediates the retention of moisture and nutrients and inhibits harmful bacteria, absorbing heavy metals and pesticides and preventing soil erosion while increasing soil pH, cationic exchange, and soil fertility. Drought and heavy metal stress often lead to the production of ROS. However, biochar significantly modifies the ROS scavenging enzymes and provides an efficient electron transferring mechanism to alleviate the toxic effects of ROS in plants. Biochar is regarded as a tool for the effective management of agricultural productivity and various environmental issues.

11. Phycochar Removes Pollutants from Soil and Wastewater

Biochar acts as a good adsorbent for removing heavy metals, dyes, and several other pollutants from wastewater. Several studies have reported the ability of algal biochar as an adsorbent of heavy metals (HMs) to help with pollution reduction [141]. For example, Poo et al. [112] prepared biochar from *Saccharina japonica* and *Sargassum fusiforme* to efficiently remove HMs from aqueous solutions. Their results showed that the high adsorption of HMs was attributed to the presence of a greater number of oxygen-containing functional groups and a higher pH. In addition, the macroalgal kelp *Saccharina japonica* biochar has special structural and functional active site groups that enhance the efficiency of adsorbing the heavy metal ions from polluted water. The efficiency of biochar for removing pollutants was attributed to increasing the effective surface sorption sites and adding superficial functional groups for the enhancement of biochar sorption ability, improving its ability to adsorb heavy metals from soils [142]. It has been reported that biochar produced from waste marine algae has a higher efficiency than other feedstocks, such as pinewood sawdust, in removing heavy metals from polluted soils [141] (Table 4). The various functional groups and porous structures of algal biochars produced at moderate temperatures can absorb pollutants more than coal fuel produced at relatively lower temperatures. The surface functional groups and higher ion exchange capacity are important mechanisms that help algal biochars remove heavy metals from contaminated soils and water [143].

The physical activation of biochar (gaseous activation) with an oxidizing agent helps open and widen inaccessible pores, enhancing the ability to adsorb pollutants from wastewater and soils [144]. Cho et al. [145] reported that steam-activated biochar from the macroalgae *Undaria pinnatifida* had a higher ability to remove or recover copper from aqueous solutions. They attributed the higher ability of algal biochar to bind to copper to the abundance of various oxygen-containing functional groups and a high exchangeable cation capacity. Similarly, steam-activated biochar from the macroalga *Porphyra tenera* improved the copper removal from aqueous solutions polluted with copper nitrate [146]. Furthermore, the steam activation of biochar from the green macroalga *Enteromorpha compressa* greatly increased the surface area and cation exchange capacity, enhancing the adsorption capacity for the removal of copper in an aqueous solution [147]. Moreover, chitosan was used to modify magnetic-kelp biochar by adding new functional groups, enhancing the efficiency of copper removal from wastewater [148] using biomass bacterial-algal residue with photosynthetic support to adsorb the mixed pollutants of heavy metals (Zn^{2+}, Cd^{2+}, Ni^{2+}, and Cu^{2+}) and salicylate.

12. Biochar Alleviates Negative Impacts of Salinity Stress

The properties of algal biochar can also help plants tolerate soil salinity. For example, biochar-promoted tomato growth under salinity stress, through the adsorption of toxic sodium ions and enhancing the release of important ions, e.g., calcium, magnesium, and potassium, can enhance the organic nature of biochar and the physicochemical characteristics of salty soil [149]. Thomas et al. [150] observed that the application of 30 g m^{-2} biochar in salty soil had no effect on the soil pH but enhanced the electrical conductivity of the soil as compared to untreated saline lands. The addition of biochar with tomato seedlings grown in saline soil considerably improved their water use efficiency, plant growth and production, and the quality of their fruits [151]. In addition, biochar applications to saline-sodic soils improved soil nutrient availability, soil cation exchange capacity, and soil surface area and reduced the sodium/potassium ratio, increasing rice yield [152]. Akhtar et al. [153] found that biochar reduced sodium absorption, alleviating the harmful effects of salinity on plants. Adding biochar to high saline soils significantly improved wheat growth.

It has been suggested that biochar could serve as a carrier, supporting the growth of beneficial microrganisms. Some studies have reported a synergistic effect between biochar and beneficial soil microbes. The exogenous application of plant-growth-promoting rhizobacteria increased plant growth and biomass under saline conditions. For example, Akhtar et al. [154] analyzed the effects of the combination of biochar and endophytic bacteria on maize plant growth and biomass under saline conditions. They found a significant improvement in leaf photosynthetic rate, stomatal conductance, and root water potential, enhancing the growth and yield of the maize plants. The mitigation of the salinity effect was attributed to the reduction of sodium absorption and increase in potassium absorption. Similarly, Nehela et al. [155] assessed the combined effects of biochar and plant-growth-promoting rhizobacteria on alleviating the negative salinity effect on maize in sodic-saline soil. The results showed a significant improvement in physicochemical properties, including increases in potassium, calcium, magnesium, and a reduction in sodium ions, by increasing the microbial activity and the concentration of soil urease and dehydrogenase. The combined effect of biochar and rhizobacteria significantly increased the leaf area index, pigment content, and total soluble sugar and improved the sodium–potassium ratio in maize plants. Furthermore, Fazal et al. [155] indicated that salinity decreased soil water availability and significantly increased osmotic stress, resulting in adverse effects on maize growth. The combined application of biochar and *Pseudomonas* sp. significantly improved moisture content and decreased electrolyte leakage, with an increased proline content, improving plant growth.

Table 4. Role of algal biochar in pollutants removal.

Environmental Pollution	Role	Reference
Air	Enhance methane uptake Absorbs Ammonia Decrease N_2O emissions	[115] [101] [156]
Water	Remove the synthetic, metallic, phenolic, pesticides pollutants	[143]
Soil	Absorb heavy metals such as lead, cadmium, copper & chromium Increase organisms involved in Nitrogen fixation and nitrification	[115,143,146,157]

13. Benefits and Limitations of Algal Biochar

This study has shown that biochar formed from algae exhibits features that make it acceptable for use as a soil amendment as well as a technique for long-term carbon sequestration [158]. When compared to many terrestrial biomass types, algae have low carbon content but higher nitrogen, phosphorus, and other nutrient content. As a result, it is fair to predict that biochar made from algal feedstocks will be high in nutrients, especially minerals. This could make algal biochar an interesting carbon sequestration and soil improvement option, as well as a high-value end product for algal biomass. The amount and content of the nutrients, on the other hand, are probably different amongst different species, and from fresh to brackish and salinity conditions [121].

According to Ross et al. [159], adding biochar to soil supplies a medium for increased microbial activity. Few studies into the applicability of algal biochar for carbon sequestration or soil fertility enrichment have been undertaken, even though the potential of both macroalgae and microalgae has previously been recognized. To maximize the value of biochar, the quality of the feedstock biomass must be higher in nutrients because the higher the nutrient content of organic waste, the greater the benefits of the biochar. Biochar is interesting in that it is a carbon-negative technique. Some of the advantages of using biochar are that it reduces soil nutrient leaching, improves nutrient availability for plants, improves runoff water quality, reduces reliance on artificial fertilizers, reduces aluminum toxicity of plant microbiomes, improves soil quality and pH, and thus contributes to bioremediation. In addition, its application leads to decreases in N_2O and CH_4 emissions from soils, thereby further reducing green greenhouse gas excretion. Biochar is remarkable because it is a "carbon-negative" process [160]. Although there are many benefits of algal biochar, there are some disadvantages to the collection of algal biomass for synthesizing biochar. The algal collection is a big hurdle in making biochar. Microalgae require specific cultivation conditions, which raises the chances of contamination and increases the cost of additional nutrients. It is a time-consuming and incompatible procedure as compared to other microorganism strains [161]. One disadvantage of biochar is that some soils may not benefit as much as others, and not all crops respond to biochar in the same manner. Depending on the agricultural practice, biochar may bind to agrochemicals and reduce their efficacy. Biochar has been demonstrated in studies to have neutral or detrimental effects on agricultural fields [162].

Biochar slows soil aging, provides essential nutrients for optimal nutrient cycling, and improves the soil water environment (Figure 3). According to Lyu et al. [163], biochar aging in soil negatively impacts the growth of earthworms and fungi, reducing nutrient cycling and soil fertility. For example, soil aging reduced the underground root biomass of *Solanum lycopersicum* and *Oryza sativa*. In addition, the application of biochar to soil has been shown to reduce soil thermal diffusivity [164]. The functional groups and redox-active metals on the surface of biochar make it more reactive than the original feedstock [165]. The biochar-derived soluble organic matter can increase Cr reduction and increase Fe/Mn oxide solubilization from soils. Because of the potential for sulfide precipitation, reductions in iron plaque, the release of As metal from Fe/Mn oxide, and other redox reactions caused by charcoal addition, these redox processes have a significant influence on the metal ion content of the soil. These redox processes are triggered by the presence of biochar. Biochar additions may impact soil pH, nutrient levels, and microbial activity, which may exert beneficial effects on crop physiological metabolism and, consequently, indirect elemental translocation. Zn carriers are numerous in rice plants and are responsible for Zn absorption and translocation [166].

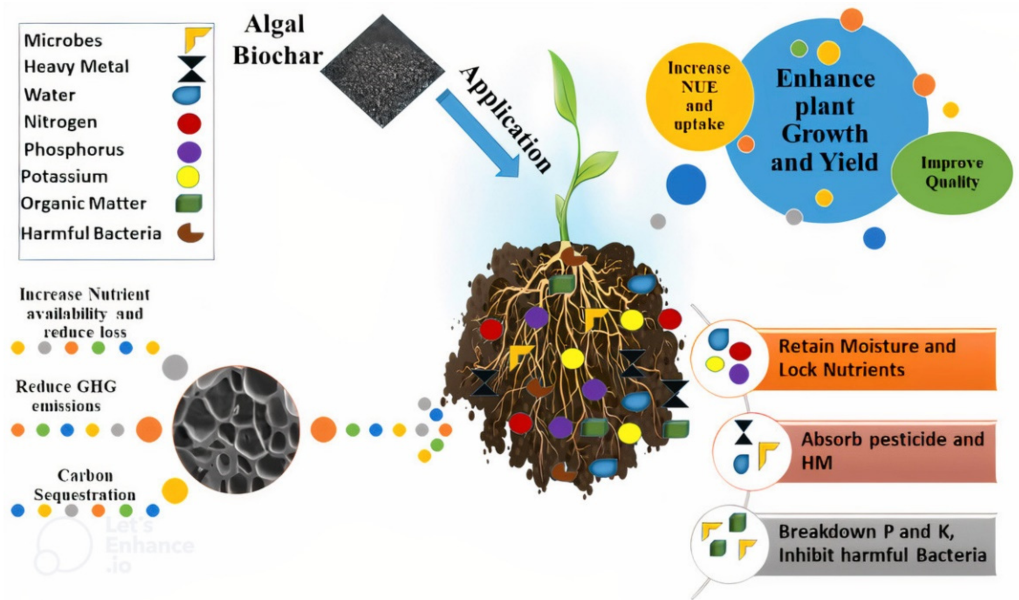

Figure 3. Prospects of algal biochar application in agricultural fields for sustainable development.

14. Production of Nanoparticles from Algae

Nanoparticles (NPs) are among the latest developed technologies that have gained interest in many disciplines, including chemistry, physics, agriculture, biotechnology, material science, medical science, and engineering. The biological synthesis of NPs (e.g., microorganisms such as bacteria, fungi, and yeast, microalgae, or plant extracts including macroalgae) is considered a safe, simple, eco-friendly approach that uses simple reducing agents instead of hazardous chemicals [167]. NPs have several applications for solving agricultural and environmental problems and maintaining sustainable agriculture and healthy ecosystems. This technology can enhance food quality and safety, reduce the overuse of fertilizers and pesticides, improve nutrient absorption from soils, and increase crop yields [168]. NPs are synthesized via two approaches: bottom-up and top-down. The first approach is through chemical reactions among atoms/ions/molecules, but the second involves mechanical methods to break down pieces of material to generate the required nanostructure sizes [169]. Micro and macroalgae are considered important sources of bioactive secondary metabolites with a wide range of biological activities [170]. Algal secondary metabolites reduce and stabilize metal salts to metal, metal oxide, or bimetallic NPs [171]. Algae can accumulate high levels of metals from their immediate environment and convert them to NPs, indicating that they are among the best organisms for the green synthesis of NPs. Additionally, Kannan et al. [172] demonstrated that algaes' high metal absorption capacity and dominance make them a low-cost raw material. Algae are increasingly being employed for the biogenic synthesis of nanoparticles due to their ease of availability and efficiency. Asmathunisha et al. [173] found a range of compounds in algal extracts, such as phenolics, pigments, flavanones, amines, terpenoids, amides, proteins, alkaloids, etc., which aided in the formation of NPs. The accessible functional groups and enzymes in algal cell walls work as reducing agents, resulting in metal and metal oxide NP reduction and synthesis under environmental circumstances.

15. Role of Algal NPs in Bioremediation

Algal synthesized NPs are used in various fields as a green approach due to lower toxicity, easy handling, cost-effectiveness, and their eco-friendly nature. As shown in (Figure 4), NPs have a vast range of applications, including medical, pharmaceutical, industrial, sensor, electrical device, cosmetic, agricultural, and bioremediation [174]. Several studies have reported a crucial role for NPs in the remediation of contaminated wastewater. For example, Ramakrishna et al. [175] used aqueous extracts of the macroalgae *Turbinaria conoides* and *Sargassum tenerrimum* as reducing and capping agents for the synthesis of gold (Au) NPs (Table 5). The Au-NPs have a good catalytic reduction efficiency in the degradation of organic dyes (Rhodamine B and Sulforhodamine 101) in the presence of sodium borohydride as a reducing agent. Au-NPs were also used to reduce nitro compounds (4-nitrophenol and p-nitroaniline). Both the organic dyes and nitro compounds are common contaminants in wastewater. In addition, silver (Ag) NPs were synthesized from an extract of the green macrophyte *Ulva lactuca* and used for the photocatalytic degradation of methyl orange dye. Among the important biological molecules in *U. lactuca* that act as capping and stabilizing agents for Ag-NPs are phenolic mixes, amines, and aromatic molecules. Ag-NPs synthesized in the extract of *U. lactuca* were used for effective photocatalytic degradation of methyl orange. Furthermore, zinc oxide NPs were synthesized from zinc acetate dehydrate from the extract of several algal species, including the brown alga *Sargassum muticum* [176], with the microalgae Chlorella zinc oxide NPs used efficiently (97%) for the photo-desulfurization of a dibenzothiophene contaminant. [177]. In addition, Prasad et al. [178] reported the role of zinc oxide NPs as a photocatalyst to selectively photodegrade cationic dyes.

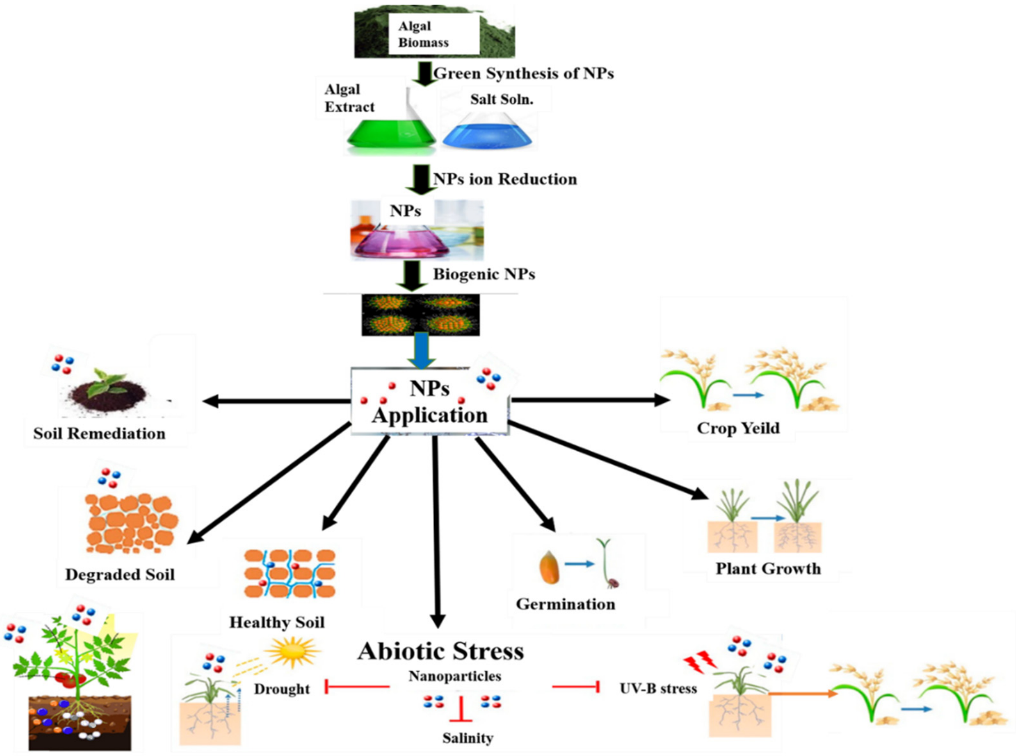

Figure 4. Nanoparticle (NP) application in plant abiotic stress resistance and management.

El-Sheekh et al. [179] used iron oxide NPs, synthesized from the aqueous extracts of three brown seaweeds (*Petalonia fascia*, *Colpomenia sinuosa*, and *Padina pavonica*), for the bioremediation of N and P, reducing the blooming of harmful algae wastewaters. The efficiency of the reduction of ferric chloride and stabilization of iron oxide NPs varied among different species. In addition, iron oxide NPs were synthesized from the extracts of several algal species, including the brown seaweed macroalgae, *Sargassum muticum*, a soil microalga, *Chlorococcum* sp., and the microalgae *Spirulina platensis* [180]. The reducing and stabilizing agents for forming iron oxide NPs were carbonyl radicals and amines of the polysaccharides and glycoproteins in the algae. Iron NPs detoxified Cr by converting the toxic Cr (VI) to the non-toxic Cr (III) [181].

16. Algal Nano Fertilizers

The agriculture industry is struggling with a fundamental problem: reduced soil fertility due to the excessive use of chemical fertilizers. NPs can be employed to create safe, efficient, and environmentally friendly nano fertilizers [182]. Synthesized nanoparticles via biochemical methods may merge to form a structure, utilizing "bottom-up" and "top-down" approaches (the bottom-up approach is also known as the self-assembly process). In a top-down method, the suitable bulk material is broken down into particles using physical or chemical procedures. The bottom-up approach to NP production is preferred because these have a parallel chemical composition and fewer issues than those produced by the top-down approach, which often results in faulty surface structures. Poor surface topography may harm the chemical and physical characteristics of nanoparticles. Wet-chemical pyrolysis methods are particularly used for the synthesis of nanoparticles, with the NPs generated in liquid media with numerous stabilizing, capping, reducing, and reactant agents. Chemical reduction, with organic or inorganic reducing chemicals either colloidally or via the sol-gel method, is commonly used to produce NPs [183]. Although these approaches produce a higher volume of NPs at a lower cost, they have some drawbacks [184]. In the physical synthesis of NPs, ultrasonication, spray pyrolysis, laser radiation, electron beam, ion implantation, and vapor phase are all utilized. These physical methods have disadvantages that make them unsuitable for nanoparticle syntheses, such as being costly, having a poor production rate, and requiring a large quantity of energy to sustain the high temperatures and pressures needed [183,184].

Table 5. Role of algal mediated nanoparticles in bioremediation and nano fertilizers.

Species	Nanoparticles	Role of Algal NPs in Bioremediation	References
Chlorella vulgaris	Ag NPs	Shows strong antifungal activity in plant	[185]
Haematococcus Candid & *chlorella* sp.	Ag NPs	Inhibited *Penicillium expansum* growth, the main cause of loss of quality and quantity of fruit	[186]
Turbinaria conoides & *Sargassum tenerrimum*	(Au) NPs	Act as bioremediation, catalytic reduction efficiency in the degradation of organic dyes	[187]
Ulva lactuca	(Ag) NPs	Used for Photocatalytic degradation of methyl orange dye	[175]
Cyanobacteria	ZnO NPs	Act as nano fertilizer have antioxidative properties	[187]
Cyanobacteria	Ag-NPs	Bactericidal activity	[188]
Chaetomorpha linum	Ag NPs	Helps in bioremediation & reduction of silver ions (Ag^+) to Ag^0	[189]
Chlorella ellipsoidea	AgNPs	Degradation of the hazardous pollutant dyes methylene blue & methyl orange	[190]
Scenedesmus obliquus	Lipid cadmium sulphide NPs	For the bioremediation of Cd^{2+} ions due to its high retention capability	[191]

17. The Beneficial Role of Algal Nanoparticles in Plant Stress Tolerance

Several field studies and controlled experiments have considered NPs for enhancing crop productivity under normal as well as stressful conditions [192]. NPs can efficiently deliver fertilizers, herbicides, and pesticides and improve soil physicochemical properties, including soil water-holding capacity. In addition, NPs can deliver specific materials, such as nucleotides, proteins, and chemicals under stressed conditions, mitigating those stress effects and improving crop growth and yield. Several studies have reported an important role of various of NPs, e.g., Ag, Ca, Fe, K, CuO, SiO_2, Se, Ti, and Zn, under controlled growth conditions: boosting crop production and resistance to abiotic stresses such as drought salinity and flood and other abiotic stresses [193].

Plant adaptation triggers biochemical, morphological, physiological, and molecular mechanisms to combat abiotic stresses. The application of nanoparticles (NPs) can help plants to withstand abiotic stresses by a concentration-dependent effect on growth and development in the plants [194]. The application of nanoparticles helps a plant's drought resistance, as observed in a study by using silica NPs in hawthorns to increase the growth of seedlings and the physiological response to drought [195]. Similar results were documented in *Triticum aestivum,* where increased starch and gluten levels in plants ultimately improved their growth under drought conditions [196]. TiO_2 also benefits plants under drought stress by increasing their biomass and maintaining their relative water content (RWC), and stimulating antioxidative enzymes [197]. Similarly, Jute seed treated with hydroxyapatite nanoparticles (CaNPs) increased drought tolerance by increasing proline synthesis [198]. According to Van Nguyen et al. [199], CuO-NPs positively influence the pigment system and the ROS-scavenging mechanism in drought-stressed maize plants. Applying the CuO-NPs at low concentrations through the roots and leaves improves crop performance by enhancing the plant's pigmentation pattern and RubisCO photosynthetic enzymes.

In *Cucurbita pepo*, for example, SiO_2 NPs enhanced plant transpiration rate, water usage efficiency (WUE), and enzyme carbonic anhydrase activity under salinity stress [200], increasing stress tolerance by decreasing the protein misfolding caused by flooding stress. The augmentation of glyoxalase II 3, alcohol dehydrogenase 1, and pyruvate decarboxylase 2 genes was seen under flooding stress; however, when exposed to Ag-NPs, the flood-induced metabolic alterations were controlled, resulting in the downregulation of all these enzymes [201]. One notable finding of proteomics was to assess the influence of Ag-NPs on the synthesis of glyoxalase II 3, regarded as an indication of cytotoxicity. When nicotinic acid and potassium nitrate (KNO3) are combined with Ag-NPs, it improved plant flood tolerance [202].

Apart from salt, drought, temperature, and heavy metal stressors, other elements such as excessive light, UV, and nutritional problems can cause oxidative stress in plants, restricting their growth and development. TiO_2 nanoparticles, for example, contribute significantly to light stress reduction by accelerating the redox process that generates superoxide and hydroxide radicals. Ultraviolet radiation is harmful to growth because it produces oxidative damage. Photosynthetic apparatus would be significantly damaged after UV-B exposure, leading to ROS formation and alterations in leaf structure, whereas SiNP treatment improved the antioxidant machinery to manage this oxidative stress [203]. As a result, NPs affect abiotic stress-induced responses in plants on several levels, and they may be employed to regulate abiotic stress in crops.

It has been reported that the application of different types of NPs can alleviate the negative effects of salt-stressed plants. For example, Zn-NPs alleviated the adverse effect of salinity in canola (*Brassica napus*) [204], potato [205], *Brassica napus,* and *B. juncea* [206]. Similarly, Ag-NPs alleviated the salinity effects during seed germination of *Pennisetum glaucum*, Khan et al. [207], in wheat seedlings [208,209], and in adult rice plants [210]. However, no studies have assessed the effect of NPs synthesized from algal extracts on salinity tolerance in salt-stressed plants.

Soil salinity negatively affects the biochemical and physiological processes that control plant growth [211]. Salt-induced crop damage is generally caused by high concentrations of Na and Cl, which are the major ions in salt-affected soils. In addition, excessive NaCl results in an osmotic and ionic imbalance in plants, leading to ROS overproduction that damages biological molecules and their metabolic activities [212]. Algal-mediated nanoparticles play a major role in increasing the activity of antioxidant enzymes such as SuperOxide Dismutase, PerOxidase, and Catalase. The application of nanoparticles affects the expression of genes involved in stress tolerance, thus helping in relieving the stress by controlling the ion toxicity, osmotic potential, and nutritional imbalance, which are all indicators of salt stress. Numerous studies have revealed that the effect of NPs on the growth and development of plants is dose-dependent. The treatment of plants with NPs at certain levels can cause harmful effects. For example, Ag-NPs induced oxidative stress that could damage the chloroplast by disturbing photosystem I activity, ultimately hindering photosynthesis in wheat seedlings [189]. In addition, Abdel Latef et al. [213] reported that lower concentrations (0.01%) were more efficient, compared to higher concentrations (0.02 and 0.03%), for enhancing several metabolites, such as enzymatic antioxidants, amino acids, soluble sugars, and proline, in salt-stressed broad bean plants. Similarly, Abbas et al. [214] reported that lower concentrations of Ce-NPs enhanced the growth and photosynthetic efficiency of wheat plants, as compared to higher concentrations, which negatively affected these processes. Furthermore, lower concentrations of Zn-NPs alleviated the salinity effect in Brassica napus and *B. juncea*, but higher concentrations caused toxicity under both saline and non-saline treatments [206].

18. Conclusions and Prospects

Anthropogenic emissions are increasing with the growing population leading to global warming, climate change, and associated biotic and abiotic stresses for crop production and food security. The present review highlighted the potential of algal biomass for carbon sequestration following its conversion to biochar (herein phycochar), which the IPCC has recommended as a negative emission technology. Authors have focused on the possibilities of using algal biomass and its products to address abiotic stresses like drought, salinity, flooding and water logging, and phytoremediation of potentially toxic elements from agricultural soils. An in-depth literature survey has been made to demonstrate the potential of algae-associated agricultural products for nutrient availability and crop production. Algal biomass converted into biochar, phyco-fertilizer and algal-mediated NPs, and nano fertilizers have demonstrated high potential for application as soil improvers and abiotic stress alleviators. Algal biomass-derived fertilizers deliver nutrients to plants and assist in plant development and soil fertility. In addition, algal-mediated nanoparticles are designed for plant growth production and minimizing nutrient loss, disease suppression, and improved yields. It has been observed that NPs can function as stress inducers and stress inhibitors and can play an important role in modifying phytohormones in response to abiotic stress. Green synthesized NPs from algal biomass are an emerging research area of nanotechnology that can hugely influence the environment regarding sustainability and future progress. Algal biomass may be cultivated in wastewater, lowering the cost of the fertilizers necessary for growth. However, a few challenges or limitations still exist concerning microalgae production on a large scale and the green synthesis of nanoparticle methodologies. Further mechanism-based research is still needed for methodological developments. Within long-term field investigations, more research attempts are required to identify the effects of phycochar, algal nanoparticles, and algal biofertilizers on soil characteristics, as all soils were not equally responsive to algal-mediated inputs.

Author Contributions: All authors contributed to the study's conception and design. Material preparation, literature search, and the collection of relevant articles and reviews were performed by all contributing authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data generated or analyzed during this study are included in this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kumar, P.; Tokas, J.; Kumar, N.; Lal, M.; Singal, H.R. Climate change consequences and its impact on agriculture and food security. *Int. J. Chem. Stud.* **2018**, *6*, 124–133.
2. Rasul, G.; Mahmood, A.; Sadiq, A.; Khan, S.I. Vulnerability of the Indus Delta to Climate Change in Pakistan. *Pak. J. Meteorol.* **2012**, *8*, 89–107.
3. Singh, P.; Kumar, N. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *J. Hydrol.* **1997**, *193*, 316–350. [CrossRef]

4. Solomon, S. *IPCC 2007: Climate Change the Physical Science Basis*; AGU Fall Meeting Abstracts U43D-01; American Geophysical Union: Washington, DC, USA, 2007.
5. Abideen, Z.; Koyro, H.W.; Huchzermeyer, B.; Ahmed, M.; Zulfiqar, F.; Egan, T.; Khan, M.A. Phragmites karka plants adopt different strategies to regulate photosynthesis and ion flux in saline and water deficit conditions. *Plant Biosyst. Int. J. Deal. All Asp. Plant Biol.* **2021**, *155*, 524–534. [CrossRef]
6. Roy, S.J.; Negrão, S.; Tester, M. Salt resistant crop plants. *Curr. Opin. Biotechnol.* **2014**, *26*, 115–124. [CrossRef] [PubMed]
7. Abideen, Z.; Koyro, H.W.; Hussain, T.; Rasheed, A.; Alwahibi, M.S.; Elshikh, M.S.; Hussain, M.I.; Zulfiqar, F.; Mansoor, S.; Abbas, Z. Biomass Production and Predicted Ethanol Yield Are Linked with Optimum Photosynthesis in *Phragmites karka* under Salinity and Drought Conditions. *Plants* **2022**, *11*, 1657. [CrossRef]
8. Lieber, M.; Chin-Hong, P.; Kelly, K.; Dandu, M.; Weiser, S.D. A systematic review and meta-analysis assessing the impact of droughts, flooding, and climate variability on malnutrition. *Glob. Public Health* **2022**, *17*, 68–82. [CrossRef]
9. Liu, Z.; Fu, B.; Zheng, X.; Liu, G. Plant biomass, soil water content and soil N: P ratio regulating soil microbial functional diversity in a temperate steppe: A regional scale study. *Soil Biol. Biochem.* **2010**, *42*, 445–450. [CrossRef]
10. Zak, D.R.; Holmes, W.E.; White, D.C.; Peacock, A.D.; Tilman, D.J.E. Plant diversity, soil microbial communities, and ecosystem function: Are there any links? *Ecology* **2003**, *84*, 2042–2050. [CrossRef]
11. Lal, S.; Bagdi, D.L.; Kakralya, B.L.; Jat, M.; Sharma, P.C. Role of brassinolide in alleviating the adverse effect of drought stress on physiology, growth and yield of green gram. *Legume Res.* **2013**, *36*, 359–363.
12. Geng, S.; Yan, D.; Zhang, T.; Weng, B.; Zhang, Z.; Qin, T.J. Effects of drought stress on agriculture soil. *Nat. Hazards* **2015**, *75*, 1997–2011. [CrossRef]
13. Ali, A.; Bajracharya, R.M.; Koirala, H.L. A review of flood risk assessment. *Int. J. Environ. Agric. Biotechnol.* **2016**, *1*, 238636. [CrossRef]
14. Dilley, M.; Chen, R.S.; Deichmann, U.; Lerner-Lam, A.L.; Arnold, M. *Natural Disaster Hotspots: A Global Risk Analysis*; World Bank Publications: Washington, DC, USA, 2005; Volume 5.
15. Cutter, S.L. Vulnerability to environmental hazards. *Prog. Hum. Geogr.* **1996**, *20*, 529–539. [CrossRef]
16. Parisi, C.; Vigani, M.; Rodríguez-Cerezo, E. Agricultural nanotechnologies: What are the current possibilities? *Nano Today* **2015**, *10*, 124–127. [CrossRef]
17. Alori, E.T.; Dare, M.O.; Babalola, O.O. Microbial Inoculants for Soil Quality and Plant Health. *Int. J. Environ. Agric. Biotechnol.* **2017**, *27*, 281–307.
18. Gaind, S. Microbial inoculants: An approach to sustainable agriculture. 2011. Available online: https://www.biotecharticles.com/Agriculture-Article/Microbial-Inoculants-an-Approach-to-Sustainable-Agriculture-940.html (accessed on 1 June 2022).
19. Carvajal-Muñoz, J.; Carmona-Garcia, C. Benefits and limitations of biofertilization in agricultural practices. *Livest. Res. Rural Dev.* **2012**, *24*, 1–8.
20. Alori, E.T.; Fawole, O. Phytoremediation of soils contaminated with aluminium and manganese by two arbuscular mycorrhizal fungi. *J. Agric. Sci.* **2012**, *4*, 246–252. [CrossRef]
21. Barsanti, L.; Gualtieri, P. *Algae: Anatomy, Biochemistry, and Biotechnology*; CRC Press: Boca Raton, FL, USA, 2005; pp. 1–320. [CrossRef]
22. Prasanna, R.; Hossain, F.; Babu, S.; Bidyarani, N.; Adak, A.; Verma, S.; Shivay, Y.S.; Nain, L. Prospecting cyanobacterial formulations as plant-growth-promoting agents for maize hybrids. *S. Afr. J. Plant Soil* **2015**, *32*, 199–207. [CrossRef]
23. Gheda, S.F.; Ahmed, D.A. Improved soil characteristics and wheat germination as influenced by inoculation of Nostoc kihlmani and Anabaena cylindrica. *Rend. Lincei* **2015**, *26*, 121–131. [CrossRef]
24. Bharti, A.; Prasanna, R.; Kumar, G.; Kumar, A.; Nain, L. Co-cultivation of cyanobacteria for raising nursery of chrysanthemum using a hydroponic system. *J. Appl. Phycol.* **2019**, *31*, 3625–3635. [CrossRef]
25. Holajjer, P.; Kamra, A.; Gaur, H.; Manjunath, M. Potential of cyanobacteria for biorational management of plant parasitic nematodes: A review. *J. Crop Prot.* **2013**, *53*, 147–151. [CrossRef]
26. Wang, R.; Peng, B.; Huang, K. The research progress of CO_2 sequestration by algal bio-fertilizer in China. *J. CO2 Util.* **2015**, *11*, 67–70. [CrossRef]
27. Yandigeri, M.S.; Yadav, A.K.; Srinivasan, R.; Kashyap, S.; Pabbi, S. Studies on mineral phosphate solubilization by cyanobacteria Westiellopsis and Anabaena. *Microbiology* **2011**, *80*, 558–565. [CrossRef]
28. Rashad, S.; El-Hassanin, A.; Mostafa, S.; El-Chaghaby, G. Cyanobacteria cultivation using olive milling wastewater for bio-fertilization of celery plant. *J. Environ. Sci. Manag.* **2019**, *5*, 167–174.
29. Mantri, N.; Patade, V.; Penna, S.; Ford, R.; Pang, E. Abiotic stress responses in plants: Present and future. In *Abiotic Stress Responses in Plants*; Springer: New York, NY, USA, 2012; pp. 1–19.
30. Jaspers, P.; Kangasjärvi, J. Reactive oxygen species in abiotic stress signaling. *Physiol. Plant* **2010**, *138*, 405–413. [CrossRef]
31. Hossain, A.; Skalicky, M.; Brestic, M.; Maitra, S.; Ashraful Alam, M.; Syed, M.A.; Islam, T. Consequences and mitigation strategies of abiotic stresses in wheat (Triticum aestivum L.) under the changing climate. *J. Agron.* **2021**, *11*, 241. [CrossRef]
32. Ammar, E.E.; Aioub, A.A.; Elesawy, A.E.; Karkour, A.M.; Mouhamed, M.S.; Amer, A.A.; El-Shershaby, N.A. Algae as Bio-fertilizers: Between current situation and future prospective. *Saudi J. Biol. Sci.* **2022**, *29*, 3083–3096. [CrossRef]
33. Khan, M.I.R.; Palakolanu, S.R.; Chopra, P.; Rajurkar, A.B.; Gupta, R.; Iqbal, N.; Maheshwari, C. Improving drought tolerance in rice: Ensuring food security through multi-dimensional approaches. *Physiol. Plant.* **2021**, *172*, 645–668. [CrossRef]

34. Zulfiqar, F.; Younis, A.; Abideen, Z.; Francini, A.; Ferrante, A. Bioregulators can improve biomass production, photosynthetic efficiency, and ornamental quality of Gazania rigens L. *Agronomy* **2019**, *9*, 773. [CrossRef]
35. Munir, N.; Hanif, M.; Dias, D.A.; Abideen, Z. The role of halophytic nano-particles towards the remediation of degraded and saline agricultural lands. *Environ. Sci. Pollut. Res.* **2021**, *28*, 60383–60405. [CrossRef]
36. Rajput, V.D.; Minkina, T.; Kumari, A.; Singh, V.K.; Verma, K.K.; Mandzhieva, S.; Keswani, C. Coping with the challenges of abiotic stress in plants: New dimensions in the field application of nanoparticles. *Plants* **2021**, *10*, 1221. [CrossRef]
37. Abideen, Z.; Hanif, M.; Munir, N.; Nielsen, B.L. Impact of Nanomaterials on the Regulation of Gene Expression and Metabolomics of Plants under Salt Stress. *Plants* **2022**, *11*, 691. [CrossRef]
38. Alotaibi, K.D.; Schoenau, J.J. Addition of biochar to a sandy desert soil: Effect on crop growth, water retention and selected properties. *Agronomy* **2019**, *9*, 327. [CrossRef]
39. Khan, Z.; Khan, M.N.; Zhang, K.; Luo, T.; Zhu, K.; Hu, L. The application of biochar alleviated the adverse effects of drought on the growth, physiology, yield and quality of rapeseed through regulation of soil status and nutrients availability. *Ind. Crops Prod.* **2021**, *171*, 113878. [CrossRef]
40. Abideen, Z.; Koyro, H.W.; Huchzermeyer, B.; Bilquees, G.U.L.; Khan, M.A. Impact of a biochar or a biochar-compost mixture on water relation, nutrient uptake and photosynthesis of *Phragmites karka*. *Pedosphere* **2020**, *30*, 466–477. [CrossRef]
41. Duarte, I.J.; Hernández, S.H.Á.; Ibañez, A.L.; Canto, A.R. Macroalgae as soil conditioners or growth promoters of *Pisum sativum* (L). *Annu. Res. Rev. Biol.* **2018**, *27*, 1–8. [CrossRef]
42. Das, P.; Khan, S.; Chaudhary, A.K.; AbdulQuadir, M.; Thaher, M.I.; Al-Jabri, H. Potential applications of algae-based bio-fertilizer. In *Biofertilizers for Sustainable Agriculture and Environment*; Giri, B., Prasad, R., Wu, Q., Varma, A., Eds.; Springer: Cham, Switzerland, 2019; pp. 41–65.
43. Guo, S.; Wang, P.; Wang, X.; Zou, M.; Liu, C.; Hao, J. Microalgae as biofertilizer in modern agriculture. In *Microalgae Biotechnology for Food, Health and High Value Products*; Springer: Singapore, 2020; pp. 397–411.
44. Coppens, J.; Grunert, O.; Van Den Hende, S.; Vanhoutte, I.; Boon, N.; Haesaert, G.; De Gelder, L. The use of microalgae as a high-value organic slow-release fertilizer results in tomatoes with increased carotenoid and sugar levels. *J. Appl. Phycol.* **2016**, *28*, 2367–2377. [CrossRef]
45. Guzmán-Murillo, M.A.; Ascencio, F.; Larrinaga-Mayoral, J.A. Germination and ROS detoxification in bell pepper (*Capsicum annuum* L.) under NaCl stress and treatment with microalgae extracts. *Protoplasma* **2013**, *250*, 33–42. [CrossRef]
46. Abd El-Baky, H.H.; El-Baz, F.K.; El Baroty, G.S. Enhancing antioxidant availability in wheat grains from plants grown under seawater stress in response to microalgae extract treatments. *J. Sci. Food Agric.* **2010**, *90*, 299–303. [CrossRef]
47. 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]
48. Salami, R.; Kordi, M.; Bolouri, P.; Delangiz, N.; Asgari Lajayer, B. Algae-based biorefinery as a sustainable renewable resource. *Circ. Econ. Environ. Prot.* **2021**, *1*, 1349–1365. [CrossRef]
49. Hasnain, M.; Munir, N.; Siddiqui, Z.S.; Ali, F.; El-Keblawy, A.; Abideen, Z. Integral Approach for the Evaluation of Sugar Cane Bio-Waste Molasses and Effects on Algal Lipids and Biodiesel Production. *Waste Biomass Valorization* **2022**, 1–20. [CrossRef]
50. Seltenrich, N. Keeping tabs on HABs: New tools for detecting, monitoring, and preventing harmful algal blooms. *Environ. Health Perspect.* **2014**, *122*, A206–A213. [CrossRef]
51. de Siqueira Castro, J.; Calijuri, M.L.; Ferreira, J.; Assemany, P.P.; Ribeiro, V.J. Microalgae based biofertilizer: A life cycle approach. *Sci. Total Environ.* **2020**, *724*, 138138. [CrossRef]
52. López-Pacheco, I.Y.; Silva-Núñez, A.; García-Perez, J.S.; Carrillo-Nieves, D.; Salinas-Salazar, C.; Castillo-Zacarías, C.; Parra-Saldívar, R. Phyco-remediation of swine wastewater as a sustainable model based on circular economy. *J. Environ. Manag.* **2021**, *278*, 111534. [CrossRef]
53. Sampathkumar, P.; Dineshkumar, R.; Rasheeq, A.A.; Arumugam, A.; Nambi, K.S. Marine microalgal extracts on cultivable crops as a considerable bio-fertilizer: A Review. *Indian J. Tradit. Knowl.* **2019**, *18*, 849–854.
54. Gören-Sağlam, N. Cyanobacteria as Biofertilizer and Their Effect under Biotic Stress. In *Plant Growth-Promoting Microbes for Sustainable Biotic and Abiotic Stress Management*; Springer: Cham, Switzerland, 2021; pp. 485–504. [CrossRef]
55. Singh, J.S. *Plant–Microbe Interactions: A Viable Tool for Agricultural Sustainability Plant Microbes Symbiosis: Applied Facets*; Arora, N.K., Ed.; Springer: Berlin/Heidelberg, Germany, 2015; p. 384.
56. Mahapatra, D.M.; Chanakya, H.; Joshi, N.; Ramachandra, T.; Murthy, G. *Algae-Based Biofertilizers: A Biorefinery Approach*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 177–196.
57. Amin, S.A.; Green, D.H.; Hart, M.C.; Küpper, F.C.; Sunda, W.G.; Carrano, C. Photolysis of iron–siderophore chelates promotes bacterial–algal mutualism. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 17071–17076. [CrossRef]
58. Round, F.E. *The Biology of the Algae*, 2nd ed.; Edward Arnold Publishers: London, UK, 1973.
59. Gonçalves, A.L. The use of microalgae and cyanobacteria in the improvement of agricultural practices: A review on their biofertilising, biostimulating and biopesticide roles. *Appl. Sci.* **2021**, *11*, 871. [CrossRef]
60. Awasthi, M.; Upadhyay, A.K.; Singh, S.; Pandey, V.P.; Dwivedi, U.N. Terpenoids as promising therapeutic molecules against Alzheimer's disease: Amyloid beta- and acetylcholinesterase-directed pharmacokinetic and molecular docking analyses. *Mol. Simul.* **2018**, *44*, 1–11. [CrossRef]

61. Singh, R.; Parihar, P.; Singh, M.; Bajguz, A.; Kumar, J.; Singh, S.; Singh, V.P.; Prasad, S.M. Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture and medicine. Current status and future prospects. *Front. Microbiol.* **2017**, *8*, 515. [CrossRef]
62. Dineshkumar, R.; Subramanian, J.; Gopalsamy, J.; Jayasingam, P.; Arumugam, A.; Kannadasan, S.; Sampathkumar, P. The Impact of Using Microalgae as Biofertilizer in Maize (*Zea mays* L.). *Waste Biomass Valorization* **2019**, *10*, 1101–1110. [CrossRef]
63. Vera, J.; Castro, J.; Gonzalez, A.; Moenne, A. Seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. *Mar. Drugs.* **2011**, *9*, 2514–2525. [CrossRef] [PubMed]
64. Arroussi, H.E.; Benhima, R.; Elbaouchi, A.; Sijilmassi, B.; Mernissi, N.E.; Aafsar, A.; Meftah-Kadmiri, I.; Bendaou, N.; Smouni, A. *Dunaliella salina* exopolysaccharides: A promising biostimulant for salt stress tolerance in tomato (*Solanum lycopersicum*). *J. Appl. Phycol.* **2018**, *30*, 2929–2941. [CrossRef]
65. Cezare-Gomes, E.A.; Mejia-da-Silva, L.d.C.; Pérez-Mora, L.S.; Matsudo, M.C.; Ferreira-Camargo, L.S.; Singh, A.K.; de Carvalho, J.C.M. Potential of Microalgae Carotenoids for Industrial Application. *Appl. Biochem. Biotechnol.* **2019**, *188*, 602–634. [CrossRef] [PubMed]
66. Lam, M.K.; Lee, K.T. Microalgae biofuels: A critical review of issues, problems and the way forward. *Biotechnol. Adv.* **2012**, *30*, 673–690. [CrossRef]
67. Kusvuran, A.; Kusvuran, S. Using of Microbial Fertilizer as Biostimulant Alleviates Damage from Drought Stress in Guar (*Cyamopsis Tetragonoloba* (L.) Taub.) Seedlings. *Int. Lett. Nat.* **2019**, *76*, 147–157. [CrossRef]
68. Pan, S.; Jeevanandam, J.; Danquah, M.K. *Benefits of Algal Extracts in Sustainable Agriculture*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 501–534.
69. Lu, Y.; Xu, J. Phytohormones in microalgae: A new opportunity for microalgal biotechnology. *Trends Plant Sci.* **2015**, *20*, 273–282. [CrossRef]
70. Ronga, D.; Biazzi, E.; Parati, K.; Carminati, D.; Carminati, E.; Tava, A. Microalgal biostimulants and biofertilisers in crop productions. *Agronomy* **2019**, *9*, 192. [CrossRef]
71. Demirbas, A.; Fatih Demirbas, M. Importance of algae oil as a source of biodiesel. In *Energy Conversion and Management*; Elsevier: Amsterdam, The Netherlands, 2011; Volume 52, pp. 163–170.
72. Sakamoto, Y.; Mori, K.; Matsuo, Y.; Mukojima, N.; Watanabe, W.; Sobaru, N.; Tamiya, S.; Nakao, T.; Hayashi, K.; Watanuki, H.J.B. Breeding of a new potato variety 'nagasaki kogane' with high eating quality, high carotenoid content, and resistance to diseases and pests. *Breed. Sci.* **2017**, *67*, 320–326. [CrossRef]
73. Haggag, W.; Hoballah, M.; Ali, R. Applications of nano biotechnological microalgae product for improve wheat productivity in semi-arid areas. *Int. J. Agric. Technol.* **2018**, *14*, 675–692.
74. Wei, G.; Jia, Q.; Chen, X.; Köllner, T.G.; Bhattacharya, D.; Wong, G.K.S.; Gershenzon, J.; Chen, F. Terpene biosynthesis in red algae is catalyzed by microbial type but not typical plant terpene synthases. *Plant Physiol.* **2019**, *179*, 382–390. [CrossRef]
75. Chittora, D.; Meena, M.; Barupal, T.; Swapnil, P.; Sharma, K. Cyanobacteria as a source of biofertilizers for sustainable agriculture. *Biochem. Biophys. Rep.* **2020**, *22*, 100737. [CrossRef]
76. Alam, S.; Seth, R.K.; Shukla, D.N. Role of blue green algae in paddy crop. *Eur. J. Exp. Biol.* **2014**, *4*, 24–28.
77. Singh, N.K.; Dhar, D.W. Cyanobacterial reclamation of salt-affected soil. In *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*; Springer: Dordrecht, The Netherlands, 2010; pp. 243–275.
78. Abideen, Z.; Qasim, M.; Hussain, T.; Rasheed, A.; Gul, B.; Koyro, H.W.; Ansari, R.; Khan, M.A. Salinity improves growth, photosynthesis and bioenergy characteristics of *Phragmites karka*. *Crop Pasture Sci.* **2018**, *69*, 944–953. [CrossRef]
79. Aljasmi, M.; El-Keblawy, A.; Mosa, K.A. Abiotic factors controllinggermination of the multipurpose invasive Prosopis pallida: Towards afor-estation of salt-afected lands in the subtropical arid Arabian desert. *Trop. Ecol.* **2021**, *62*, 116–125. [CrossRef]
80. El-Keblawy, A.; Aljasmi, M.; Gairola, S.; Mosa, K.A.; Hameed, A. Provenance determines salinity tolerance and germination requirements of the multipurpose tree *Prosopis juliflora* seeds. *Arid Land Res. Manag.* **2021**, *35*, 446–462. [CrossRef]
81. Rodríguez, A.A.; Stella, A.M.; Storni, M.M.; Zulpa, G.; Zaccaro, M.C. Effects of cyanobacterial extracellular products and gibberellic acid on salinity tolerance in *Oryza sativa* L. *Saline Syst.* **2006**, *2*, 7. [CrossRef]
82. Saadatnia, H.; Riahi, H. Cyanobacteria from paddy fields in Iran as a biofertilizer in rice plants. *Plant Soil Environ.* **2009**, *55*, 207–212. [CrossRef]
83. Chatterjee, A.; Singh, S.; Agrawal, C.; Yadav, S.; Rai, R.; Rai, L.C. Role of algae as a biofertilizer. In *Algal Green Chem*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 189–200.
84. Chen, M.; Yang, Z.; Liu, J.; Zhu, T.; Wei, X.; Fan, H.; Wang, B. Adaptation mechanism of salt excluders under saline conditions and its applications. *Int. J. Mol. Sci.* **2018**, *19*, 3668. [CrossRef]
85. El Semary, N.A.; Alouane, M.H.H.; Nasr, O.; Aldayel, M.F.; Alhaweti, F.H.; Ahmed, F. Salinity Stress Mitigation Using Encapsulated Biofertilizers for Sustainable Agriculture. *Sustainability* **2020**, *12*, 9218. [CrossRef]
86. Kannaiyan, S.; Aruna, S.; Kumari, S.M.P.; Hall, D.O. Immobilized cyanobacteria as a biofertilizer for rice crops; Intl. Conference on Applied Algology, Knysna, South Africa, April 1996. *J. Appl. Phycol.* **1997**, *9*, 167–174. [CrossRef]
87. Fathi, A.; Tari, D.B. Effect of drought stress and its mechanism in plants. *Int. J. Life Sci.* **2016**, *10*, 1. [CrossRef]
88. Benjamin, J.; Nielsen, D. Water deficit effects on root distribution of soybean, field pea and chickpea. *Field Crops Res.* **2006**, *97*, 248–253. [CrossRef]

89. Praba, M.L.; Cairns, J.E.; Babu, R.C.; Lafitte, H.R. Identification of physiological traits underlying cultivar differences in drought tolerance in rice and wheat. *J. Agron. Crop Sci.* **2009**, *195*, 30–46. [CrossRef]
90. Sotelo-Cuitiva, Y.M.; Restrepo-Díaz, H.; García-Castro, A.; Ramírez-Godoy, A.; Flórez-Roncancio, V.J. Effect of Kaolin Film Particle Applications (Surround WP®) and Water Deficit on Physiological Characteristics in Rose Cut Plants (*Rose* spp L.). *Am. J. Plant Sci.* **2011**, *2*, 354–358. [CrossRef]
91. Farooq, M.; Wahid, A.; Kobayashi, N.; Fujita, D.; Basra, S.M.A. Plant drought stress: Effects, mechanisms and management. *J. Sustain. Agric.* **2009**, *29*, 153–188.
92. Bello, A.S.; Saadaoui, I.; Ben-Hamadou, R. "Beyond the Source of Bioenergy": Microalgae in Modern Agriculture as a Biostimulant, Biofertilizer, and Anti-Abiotic Stress. *J. Agron.* **2021**, *11*, 1610. [CrossRef]
93. Duo, L.A.; Liu, C.X.; Zhao, S.L. Alleviation of drought stress in turfgrass by the combined application of nano-compost and microbes from compost. *Russ. J. Plant Physiol.* **2018**, *65*, 419–426. [CrossRef]
94. Kusvuran, S. Microalgae (*Chlorella vulgaris* Beijerinck) alleviates drought stress of broccoli plants by improving nutrient uptake, secondary metabolites, and antioxidative defense system. *Hortic. Plant J.* **2021**, *7*, 221–231. [CrossRef]
95. Chiaiese, P.; Corrado, G.; Colla, G.; Kyriacou, M.C.; Rouphael, Y. Renewable sources of plant biostimulation: Microalgae as a sustainable means to improve crop performance. *Front. Plant Sci.* **2018**, *9*, 1782. [CrossRef] [PubMed]
96. Chaiwong, C.; Koottatep, T.; Polprasert, C. Effects of specific wavelengths of lights on performance of biofilm photobioreactor for treating septic tank effluent. *J. Water Process Eng.* **2021**, *40*, 101907. [CrossRef]
97. Chaiwong, K.; Kiatsiriroat, T.; Vorayos, N.; Thararax, C. Biochar production from freshwater algae by slow pyrolysis. *Maejo Int. J. Sci. Technol.* **2012**, *6*, 186–195.
98. 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]
99. 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]
100. Das, P.; Chandramohan, V.P.; Mathimani, T.; Pugazhendhi, A. Recent advances in thermochemical methods for the conversion of algal biomass to energy. *Sci. Total Environ.* **2021**, *766*, 144–608. [CrossRef]
101. Yu, K.L.; Chen, W.H.; Sheen, H.K.; Chang, J.-S.; Lin, C.S.; Ong, H.C.; Show, P.L.; Ng, E.P.; Ling, T.C. Production of microalgal biochar and reducing sugar using wet torrefaction with microwave-assisted heating and acid hydrolysis pretreatment. *Renew. Energy* **2020**, *156*, 349–360. [CrossRef]
102. 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*, 119–944. [CrossRef]
103. Norouzi, O.; Jafarian, S.; Safari, F.; Tavasoli, A.; Nejati, B. Promotion of hydrogen-rich gas and phenolic-rich bio-oil production from green macroalgae Cladophora glomerata via pyrolysis over its bio-char. *Bioresour. Technol.* **2016**, *219*, 643–651. [CrossRef]
104. Torri, C.; Samorì, C.; Adamiano, A.; Fabbri, D.; Faraloni, C.; Torzillo, G. Preliminary investigation on the production of fuels and biochar from *Chlamydomonas reinhardtii* biomass residue after bio-hydrogen production. *Bioresour. Technol.* **2011**, *102*, 8707–8713. [CrossRef]
105. Sharma, R.; Jasrotia, K.; Singh, N.; Ghosh, P.; Sharma, N.R.; Singh, J.; Kumar, A. A comprehensive review on hydrothermal carbonization of biomass and its applications. *Afr. J. Chem.* **2020**, *3*, 1–19. [CrossRef]
106. Roy, P.; Dias, G. Prospects for pyrolysis technologies in the bioenergy sector: A review. *Renew. Sustain. Energy Rev.* **2017**, *77*, 59–69. [CrossRef]
107. Chen, W.H.; Lin, B.J.; Huang, M.Y.; Chang, J.S. Thermochemical conversion of microalgal biomass into biofuels: A review. *Bioresour. Technol.* **2015**, *184*, 314–327. [CrossRef]
108. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
109. Dissanayake, P.D.; You, S.; Igalavithana, A.D.; Xia, Y.; Bhatnagar, A.; Gupta, S.; Ok, Y.S. Biochar-based adsorbents for carbon dioxide capture: A critical review. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109582. [CrossRef]
110. Cheng, N.; Wang, B.; Wu, P.; Lee, X.; Xing, Y.; Chen, M.; Gao, B. Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environ. Pollut.* **2021**, *273*, 116448. [CrossRef]
111. Zhang, L.; Li, F.; Kuroki, A.; Loh, K.C.; Wang, C.H.; Dai, Y.; Tong, Y.W. Methane yield enhancement of mesophilic and thermophilic anaerobic co-digestion of algal biomass and food waste using algal biochar: Semi-continuous operation and microbial community analysis. *Bioresour. Technol.* **2020**, *302*, 122–892. [CrossRef]
112. Gollakota, A.; Kishore, N.; Gu, S. A review on hydrothermal liquefaction of biomass. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1378–1392. [CrossRef]
113. 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]
114. Michalak, I.; Messyasz, B. Concise review of *Cladophora* spp. macroalgae of commercial interest. *J. Appl. Phycol.* **2021**, *33*, 133–166. [CrossRef]

115. Mona, S.; Malyan, S.K.; Saini, N.; Deepak, B.; Pugazhendhi, A.; Kumar, S.S. Towards sustainable agriculture with carbon sequestration, and greenhouse gas mitigation using algal biochar. *Chemosphere* **2021**, *275*, 129–856. [CrossRef] [PubMed]
116. 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*, 119–190. [CrossRef]
117. Vardon, D.R.; Sharma, B.; Scott, J.; Yu, G.; Wang, Z.; Schideman, L.; Zhang, Y.; Strathmann, T.J. Chemical properties of biocrude oil from the hydrothermal liquefaction of Spirulina algae, swine manure, and digested anaerobic sludge. *Bioresour. Technol.* **2011**, *102*, 8295–8303. [CrossRef] [PubMed]
118. Neveux, N.; Yuen, A.; Jazrawi, C.; Magnusson, M.; Haynes, B.; Masters, A.; Montoya, A.; Paul, N.; Maschmeyer, T.; De Nys, R. Biocrude yield and productivity from the hydrothermal liquefaction of marine and freshwater green macroalgae. *Bioresour. Technol.* **2014**, *155*, 334–341. [CrossRef] [PubMed]
119. Huang, Y.; Chen, Y.; Xie, J.; Liu, H.; Yin, X.; Wu, C. Bio-oil production from hydrothermal liquefaction of high-protein high-ash microalgae including wild Cyanobacteria sp. and cultivated *Bacillariophyta* sp. *Fuel* **2016**, *183*, 9–19. [CrossRef]
120. Trivedi, N.; Gupta, V.; Reddy, C.; Jha, B. Enzymatic hydrolysis and production of bioethanol from common macrophytic green alga *Ulva fasciata* Delile. *Bioresour. Technol.* **2013**, *150*, 106–112. [CrossRef]
121. Bird, M.I.; Wurster, C.M.; de Paula Silva, P.H.; Bass, A.M.; De Nys, R. Algal biochar production and properties. *Bioresour. Technol.* **2011**, *102*, 1886–1891. [CrossRef]
122. Lehmann, J.; Joseph, S. (Eds.) *Biochar for Environmental Management: Science and Technology*; Earthscan: London, UK, 2009; pp. 1–12.
123. Matovic, D. Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy J.* **2011**, *36*, 2011–2016. [CrossRef]
124. Ghani, W.A.W.A.K.; Mohd, A.; da Silva, G.; Bachmann, R.T.; Taufiq-Yap, Y.H.; Rashid, U. Biochar production from waste rubber-wood-sawdust and its potential use in C sequestration: Chemical and physical characterization. *Ind. Crops Prod.* **2013**, *44*, 18–24. [CrossRef]
125. Suganya, T.; Varman, M.; Masjuki, H.; Renganathan, S. Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renew. Sustain. Energy Rev.* **2016**, *55*, 909–941. [CrossRef]
126. Kambo, H.S.; Dutta, A. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties, and applications. *Renew. Sustain. Energy Rev.* **2015**, *45*, 359–378. [CrossRef]
127. Fahad, S.; Bajwa, A.; Nazir, U.; Anjum, S.; Farooq, A.; Zohaib, A.; Sadia, S.; Nasim, W.; Adkins, S.; Saud, S.; et al. Crop production under drought and heat stress: Plant responses and management options. *Front. Plant Sci.* **2017**, *8*, 1147. [CrossRef]
128. Abideen, Z.; Koyro, H.W.; Huchzermeyer, B.; Ansari, R.; Zulfiqar, F.; Gul, B.J.P.B. Ameliorating effects of biochar on photosynthetic efficiency and antioxidant defence of Phragmites karka under drought stress. *Plant Biol.* **2020**, *22*, 259–266. [CrossRef]
129. Ullah, N.; Ditta, A.; Imtiaz, M.; Li, X.; Jan, A.U.; Mehmood, S.; Rizwan, M. Appraisal for organic amendments and plant growth-promoting rhizobacteria to enhance crop productivity under drought stress: A review. *J. Agron. Crop Sci.* **2021**, *42*, 770–781. [CrossRef]
130. Akhtar, S.S.; Li, G.; Andersen, M.N.; Liu, F. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manag.* **2014**, *138*, 37–44. [CrossRef]
131. Haider, G.; Steffens, D.; Moser, G.; Müller, C.; Kammann, C.I. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. *Agric. Ecosyst. Environ.* **2017**, *237*, 80–94. [CrossRef]
132. Ullah, N.; Ditta, A.; Khalid, A.; Mehmood, S.; Rizwan, M.S.; Ashraf, M.; Mubeen, F.; Imtiaz, M.; Iqbal, M.M. Integrated effect of algal biochar and plant growth promoting Rhizobacteria on physiology and growth of maize under deficit irrigations. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 346–356. [CrossRef]
133. Haider, G.; Koyro, H.W.; Azam, F.; Steffens, D.; Müller, C.; Kammann, C. Biochar but not humic acid product amendment affected maize yields via improving plant-soil moisture relations. *Plant Soil* **2015**, *395*, 141–157. [CrossRef]
134. Olmo, M.; Alburquerque, J.A.; Barrón, V.; Del Campillo, M.C.; Gallardo, A.; Fuentes, M.; Villar, R. Wheat growth and yield responses to biochar addition under Mediterranean climate conditions. *Biol. Fertil. Soils* **2014**, *50*, 1177–1187. [CrossRef]
135. Haider, I.; Raza, M.A.S.; Iqbal, R.; Aslam, M.U.; Habib-ur-Rahman, M.; Raja, S.; Ahmad, S. Potential effects of biochar application on mitigating the drought stress implications on wheat (*Triticum aestivum* L.) under various growth stages. *J. Saudi Chem. Soc.* **2020**, *24*, 974–981. [CrossRef]
136. Keshavarz Afshar, R.; Hashemi, M.; Da Costa, M.; Spargo, J.; Sadeghpour, A. Biochar application and drought stress effects on physiological characteristics of *Silybum marianum*. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 743–752. [CrossRef]
137. Tayyab, M.; Islam, W.; Khalil, F.; Ziqin, P.; Caifang, Z.; Arafat, Y.; Hua, Z. Biochar: An efficient way to manage low water availability in plants. *Appl. Ecol. Environ. Res.* **2018**, *16*, 2565–2583. [CrossRef]
138. De Silva, N.D.G.; Cholewa, E.; Ryser, P. Effects of combined drought and heavy metal stresses on xylem structure and hydraulic conductivity in red maple (*Acer rubrum* L.). *J. Exp. Bot.* **2012**, *63*, 5957–5966. [CrossRef]
139. Mansoor, S.; Kour, N.; Manhas, S.; Zahid, S.; Wani, O.A.; Sharma, V.; Ahmad, P. Biochar as a tool for effective management of drought and heavy metal toxicity. *Chemosphere* **2021**, *271*, 129458. [CrossRef]
140. Abbas, T.; Rizwan, M.; Ali, S.; Adrees, M.; Mahmood, A.; Zia-ur-Rehman, M.; Qayyum, M.F. Biochar application increased the growth and yield and reduced cadmium in drought stressed wheat grown in an aged, contaminated soil. *Ecotoxicol. Environ. Saf.* **2018**, *148*, 825–833. [CrossRef] [PubMed]

141. Karthik, A.; Hussainy, S.A.H.; Rajasekar, M. Comprehensive study on biochar and its effect on Soil properties: A review. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 459–477. [CrossRef]
142. Xue, Y.; Gao, B.; Yao, Y.; Inyang, M.; Zhang, M.; Zimmerman, A.R.; Ro, K.S. Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. *J. Chem. Eng.* **2012**, *200*, 673–680.
143. 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]
144. Sajjadi, B.; Chen, W.Y.; Egiebor, N.O. A comprehensive review on physical activation of biochar for energy and environmental applications. *Rev. Chem. Eng.* **2019**, *35*, 735–776. [CrossRef]
145. Cho, H.J.; Baek, K.; Jeon, J.K.; Park, S.H.; Suh, D.J.; Park, Y.K. Removal characteristics of copper by marine macro-algae-derived chars. *J. Chem. Eng.* **2013**, *217*, 205–211.
146. Singh, A.; Sharma, R.; Pant, D.; Malaviya, P. Engineered algal biochar for contaminant remediation and electrochemical applications. *Sci. Total Environ.* **2021**, *774*, 145–676.
147. Kim, B.S.; Lee, H.W.; Park, S.H. Removal of Cu^{2+} by biochars derived from green macroalgae. *Environ. Sci. Pollut. Res.* **2016**, *23*, 985–994. [CrossRef]
148. Son, E.B.; Poo, K.M.; Mohamed, H.O.; Choi, Y.J.; Cho, W.C.; Chae, K.J. A novel approach to developing a reusable marine macro-algae adsorbent with chitosan and ferric oxide for simultaneous efficient heavy metal removal and easy magnetic separation. *Bioresour. Technol.* **2018**, *259*, 381–387. [CrossRef]
149. Murtaza, G.; Ahmed, Z.; Usman, M.; Tariq, W.; Ullah, Z.; Shareef, M.; Ditta, A. Biochar induced modifications in soil properties and its impacts on crop growth and production. *J. Plant Nutr.* **2021**, *44*, 1677–1691. [CrossRef]
150. Thomas, S.C.; Frye, S.; Gale, N.; Garmon, M.; Launchbury, R.; Machado, N.; Melamed, S.; Murray, J.; Petroff, A.; Winsborough, C. Biochar mitigates negative effects of salt additions on two herbaceous plant species. *J. Environ. Manag.* **2013**, *129*, 62–68. [CrossRef]
151. Mulcahy, D.N.; Mulcahy, D.L.; Dietz, D. Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *J. Arid Environ.* **2013**, *88*, 222–225. [CrossRef]
152. Hu, Q.; Jung, J.; Chen, D.; Leong, K.; Song, S.; Li, F.; Mohan, B.C.; Yao, Z.; Prabhakar, A.K.; Lin, X.H.; et al. Biochar industry to circular economy. *Sci. Total Environ.* **2021**, *757*, 143820. [CrossRef]
153. Akhtar, S.S.; Andersen, M.N.; Liu, F. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agric. Water Manag.* **2015**, *158*, 61–68. [CrossRef]
154. Akhtar, S.S.; Andersen, M.N.; Naveed, M.; Zahir, Z.A.; Liu, F. Interactive effect of biochar and plant growth-promoting bacterial endophytes on ameliorating salinity stress in maize. *Funct. Plant Biol.* **2015**, *42*, 770–781. [CrossRef]
155. Nehela, Y.; Mazrou, Y.S.; Alshaal, T.; Rady, A.; El-Sherif, A.; Omara, A.E.D.; Hafez, E.M. The Integrated Amendment of Sodic-Saline Soils Using Biochar and Plant Growth-Promoting Rhizobacteria Enhances Maize (*Zea mays* L.) Resilience to Water Salinity. *Plants* **2021**, *10*, 1960. [CrossRef]
156. Fazal, A.; Bano, A. Role of plant growth-promoting rhizobacteria (PGPR), biochar, and chemical fertilizer under salinity stress. Commun. *Soil Sci. Plant Anal.* **2016**, *47*, 1985–1993. [CrossRef]
157. Gwenzi, W.; Chaukura, N.; Wenga, T.; Mtisi, M. Biochars as media for air pollution control systems: Contaminant removal, applications and future research directions. *Sci. Total Environ.* **2020**, *753*, 142–249. [CrossRef]
158. Li, H.; Watson, J.; Zhang, Y.; Lu, H.; Liu, Z. Environment-enhancing process for algal wastewater treatment, heavy metal control and hydrothermal biofuel production: A critical review. *Bioresour. Technol.* **2020**, *298*, 122–421. [CrossRef]
159. Ross, A.; Jones, J.; Kubacki, M.; Bridgeman, T. Classification of macroalgae as fuel and its thermochemical behaviour. *Bioresour. Technol.* **2008**, *99*, 6494–6504. [CrossRef]
160. Maraseni, T.N. Biochar: Maximising the benefits. *Int. J. Environ. Sci.* **2010**, *67*, 319–327. [CrossRef]
161. Mathimani, T.; Mallick, N. A comprehensive review on harvesting of microalgae for biodiesel–key challenges and future directions. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1103–1120. [CrossRef]
162. Kuppusamy, S.; Thavamani, P.; Megharaj, M.; Venkateswarlu, K.; Naidu, R. Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. *Environ. Int.* **2016**, *87*, 1–12. [CrossRef]
163. Lyu, H.; Zhang, Q.; Shen, B. Application of biochar and its composites in catalysis. *Chemosphere* **2020**, *240*, 124842. [CrossRef]
164. Kavitha, M.; Raja, M.; Perumal, P. Evaluation of probiotic potential of Bacillus spp. isolated from the digestive tract of freshwater fish *Labeo calbasu* (Hamilton, 1822). *Aquac. Rep.* **2018**, *11*, 59–69. [CrossRef]
165. Yuan, Y.; Bolan, N.; Prévoteau, A.; Vithanage, M.; Biswas, J.K.; Ok, Y.S.; Wang, H. Applications of biochar in redox-mediated reactions. *Bioresour. Technol.* **2017**, *246*, 271–281. [CrossRef]
166. Jing, F.; Chen, C.; Chen, X.; Liu, W.; Wen, X.; Hu, S.; Yang, Z.; Guo, B.; Xu, Y.; Yu, Q. Effects of wheat straw derived biochar on cadmium availability in a paddy soil and its accumulation in rice. *Environ. Pollut.* **2020**, *257*, 113592. [CrossRef]
167. Uzair, B.; Liaqat, A.; Iqbal, H.; Menaa, B.; Razzaq, A.; Thiripuranathar, G.; Fatima Rana, N.; Menaa, F. Green and cost-effective synthesis of metallic nanoparticles by algae: Safe methods for translational medicine. *J. Bioeng.* **2020**, *7*, 129. [CrossRef] [PubMed]
168. Prasad, R.; Bhattacharyya, A.; Nguyen, Q.D. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Front. Microbiol.* **2017**, *8*, 1014. [CrossRef] [PubMed]
169. Srivastava, S.; Bhargava, A. *Green Nanoparticles: The Future of Nanobiotechnology*; Springer: Berlin/Heidelberg, Germany, 2022.

170. Arya, A.; Mishra, V.; Chundawat, T.S. Green synthesis of silver nanoparticles from green algae (*Botryococcus braunii*) and its catalytic behavior for the synthesis of benzimidazoles. *Chem. Data Collect.* **2019**, *20*, 100190. [CrossRef]
171. Korbekandi, H.; Ashari, Z.; Iravani, S.; Abbasi, S. Optimization of biological synthesis of silver nanoparticles using Fusarium oxysporum. *Iran. J. Pharm. Sci.* **2013**, *12*, 289.
172. Kannan, R.R.R.; Arumugam, R.; Ramya, D.; Manivannan, K.; Anantharaman, P. Green synthesis of silver nanoparticles using marine macroalga *Chaetomorpha linum*. *Appl. Nanosci.* **2013**, *3*, 229–233. [CrossRef]
173. Asmathunisha, N.; Kathiresan, K.J.C.; Biointerfaces, S.B. A review on biosynthesis of nanoparticles by marine organisms. *Colloids Surf. B Biointerfaces* **2013**, *103*, 283–287. [CrossRef]
174. AlNadhari, S.; Al-Enazi, N.M.; Alshehrei, F.; Ameen, F. A review on biogenic synthesis of metal nanoparticles using marine algae and its applications. *Environ. Res.* **2021**, *194*, 110672. [CrossRef]
175. Ramakrishna, M.; Rajesh Babu, D.; Gengan, R.M.; Chandra, S.; Nageswara Rao, G. Green synthesis of gold nanoparticles using marine algae and evaluation of their catalytic activity. *J. Nanostruct. Chem.* **2016**, *6*, 1–13. [CrossRef]
176. Azizi, S.; Ahmad, M.B.; Namvar, F.; Mohamad, R. Green biosynthesis and characterization of zinc oxide nanoparticles using brown marine macroalga *Sargassum Muticum* aqueous extract. *Mater. Lett.* **2014**, *116*, 275–277. [CrossRef]
177. Khalafi, T.; Buazar, F.; Ghanemi, K. Phycosynthesis and enhanced photocatalytic activity of zinc oxide nanoparticles toward organosulfur pollutants. *Sci. Rep.* **2019**, *9*, 6866. [CrossRef]
178. Prasad, A.R.; Garvasis, J.; Oruvil, S.K.; Joseph, A. Bio-inspired green synthesis of zinc oxide nanoparticles using Abelmoschus esculentus mucilage and selective degradation of cationic dye pollutants. *J. Phys. Chem. Solids* **2019**, *127*, 265–274. [CrossRef]
179. El-Sheekh, M.M.; El-Kassas, H.Y.; Shams El-Din, N.G.; Eissa, D.I.; El-Sherbiny, B.A. Green synthesis, characterization applications of iron oxide nanoparticles for antialgal and wastewater bioremediation using three brown algae. *Int. J. Phytoremediat.* **2021**, *23*, 1538–1552. [CrossRef]
180. Madhavi, V.; Prasad, T.N.; Reddy, A.V.; Ravindra Reddy, B.; Madhavi, G. Application of phytogenic zero valent iron nanoparticles in the adsorption of hexavalent chromium. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2013**, *116*, 17–25. [CrossRef]
181. Shalaby, S.M.; Madkour, F.F.; El-Kassas, H.Y.; Mohamed, A.A.; Elgarahy, A.M. Green synthesis of recyclable iron oxide nanoparticles using Spirulina platensis microalgae for adsorptive removal of cationic and anionic dyes. *Environ. Sci. Pollut. Res.* **2021**, *28*, 65549–65572. [CrossRef]
182. Subramaniyam, V.; Subashchandrabose, S.R.; Thavamani, P.; Megharaj, M.; Chen, Z.; Naidu, R. *Chlorococcum* sp. MM11—A novel phyco-nanofactory for the synthesis of iron nanoparticles. *J. Appl. Phycol.* **2015**, *27*, 1861–1869. [CrossRef]
183. Salem, S.S.; Fouda, A. Green synthesis of metallic nanoparticles and their prospective biotechnological applications: An overview. *Biol. Trace Elem. Res.* **2021**, *199*, 344–370. [CrossRef]
184. Sharma, G.; Pandey, S.; Ghatak, S.; Watal, G.; Rai, P.K. *Potential of Spectroscopic Techniques in the Characterization of "Green Nanomaterials"*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 59–77.
185. Thakkar, K.N.; Mhatre, S.S. Parikh, biology and medicine. Biological synthesis of metallic nanoparticles. *Nanomed. Nanotechnol. Biol. Med.* **2010**, *6*, 257–262. [CrossRef]
186. El-Moslamy, S.; Kabeil, S.; Hafez, E. Bioprocess Development for Chlorella vulgaris cultivation and biosynthesis of anti phytopathogens silver nanoparticles. *J. Nanomater. Mol. Nanotechnol.* **2016**, *5*, 2. [CrossRef]
187. Terra, A.L.M.; Kosinski, R.d.C.; Moreira, J.B.; Costa, J.A.V.; Morais, M.G.d. Microalgae biosynthesis of silver nanoparticles for application in the control of agricultural pathogens. *J. Environ. Sci. Health Part B* **2019**, *54*, 709–716. [CrossRef]
188. Annamalai, J.; Shanmugam, J.; Nallamuthu, T. Salt stress enhancing the production of Phytochemicals in *Chlorella vulgaris* and *Chlamydomonas reinhardtii*. *J. Algal Biomass Util.* **2016**, *7*, 37–44.
189. Hamida, R.S.; Ali, M.A.; Redhwan, A.; Bin-Meferij, M.M. Cyanobacteria—A promising platform in green nanotechnology: A review on nanoparticles fabrication and their prospective applications. *Int. J. Nanomed.* **2020**, *15*, 6033–6066. [CrossRef]
190. Paulkumar, K.; Rajeshkumar, S.; Gnanajobitha, G.; Vanaja, M.; Malarkodi, C.; Annadurai, G. Eco-friendly synthesis of silver chloride nanoparticles using Klebsiella planticola (MTCC 2277). International. *Int. J. Green Chem. Bioprocess* **2013**, *3*, 12–16.
191. Priyadharshini, R.I.; Prasannaraj, G.; Geetha, N.; Venkatachalam, P. Microwave-mediated extracellular synthesis of metallic silver and zinc oxide nanoparticles using macro-algae (*Gracilaria edulis*) extracts and its anticancer activity against human PC3 cell lines. *Appl. Biochem. Biotechnol.* **2014**, *174*, 2777–2790. [CrossRef]
192. Jena, J.; Pradhan, N.; Aishvarya, V.; Nayak, R.R.; Dash, B.P.; Sukla, L.B.; Panda, P.K.; Mishra, B.K. Biological sequestration and retention of cadmium as CdS nanoparticles by the microalga Scenedesmus-24J. *J. Appl. Phycol.* **2015**, *27*, 2251–2260. [CrossRef]
193. Zulfiqar, F.; Ashraf, M. Nanoparticles potentially mediate salt stress tolerance in plants. *Plant Physiol. Biochem.* **2021**, *160*, 257–268. [CrossRef]
194. Rastogi, A.; Tripathi, D.K.; Yadav, S.; Chauhan, D.K.; Živčák, M.; Ghorbanpour, M.; Restic, M. Application of silicon nanoparticles in agriculture. *3 Biotech* **2019**, *9*, 90. [CrossRef]
195. Ashkavand, P.; Tabari, M.; Zarafshar, M.; Tomásková, I.; Struve, D. Effect of SiO_2 nanoparticles on drought resistance in hawthorn seedlings. *Leśne Pr. Badaw.* **2015**, *76*, 350–359. [CrossRef]
196. Sarraf, M.; Vishwakarma, K.; Kumar, V.; Arif, N.; Das, S.; Johnson, R.; Hasanuzzaman, M. Metal/metalloid-based nanomaterials for plant abiotic stress tolerance: An overview of the mechanisms. *Plants* **2022**, *11*, 316. [CrossRef]
197. Dimkpa, C.O.; Bindraban, P.S.; Fugice, J.; Agyin-Birikorang, S.; Singh, U.; Hellums, D. Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agron. Sustain. Dev.* **2017**, *37*, 5. [CrossRef]

198. Jaberzadeh, A.; Moaveni, P.; Moghadam, H.R.; Zahedi, H. Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2013**, *41*, 201–207.
199. Van Nguyen, D.; Nguyen, H.M.; Le, N.T.; Nguyen, K.H.; Nguyen, H.T.; Le, H.M.; Nguyen, A.T.; Dinh, N.T.T.; Hoang, S.A.; Van Ha, C. Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *J. Plant Growth Regul.* **2022**, *41*, 364–375. [CrossRef]
200. Hashimoto, T.; Mustafa, G.; Nishiuchi, T.; Komatsu, S. Comparative analysis of the effect of inorganic and organic chemicals with silver nanoparticles on soybean under flooding stress. *Int. J. Mol. Sci.* **2020**, *21*, 1300. [CrossRef] [PubMed]
201. Faraji, J.; Sepehri, A. Exogenous nitric oxide improves the protective effects of TiO_2 nanoparticles on growth, antioxidant system, and photosynthetic performance of wheat seedlings under drought stress. *J. Soil. Sci. Plant Nutr.* **2020**, *20*, 703–714. [CrossRef]
202. Das, A.; Ray, R.; Mandal, N.; Chakrabarti, K. An analysis of transcripts and enzyme profiles in drought stressed jute (*Corchorus capsularis*) and rice (*Oryza sativa*) seedlings treated with $CaCl_2$, hydroxyapatite nano-particle and β-amino butyric acid. *Plant Growth Regul.* **2016**, *79*, 401–412. [CrossRef]
203. Siddiqui, M.H.; Al-Whaibi, M.H.; Faisal, M.; Al Sahli, A.A. Nano-silicon dioxide mitigates the adverse effects of salt stress on *Cucurbita pepo* L. *Environ. Toxicol. Chem.* **2014**, *33*, 2429–2437. [CrossRef]
204. Elsheery, N.I.; Helaly, M.N.; El-Hoseiny, H.M.; Alam-Eldein, S.M. Zinc oxide and silicone nanoparticles to improve the resistance mechanism and annual productivity of salt-stressed mango trees. *Agronomy* **2020**, *10*, 558. [CrossRef]
205. Mohamed, A.K.S.H.; Qayyum, M.F.; Abdel-Hadi, A.; Rehman, R.A.; Ali, S.; Rizwan, M. Interactive effect of salinity and silver nanoparticles on photosynthetic and biochemical parameters of wheat. *Arch. Agron. Soil Sci.* **2017**, *63*, 1736–1747. [CrossRef]
206. Djanaguiraman, M.; Nair, R.; Giraldo, J.P.; Prasad, P.V.V. Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. *ACS Omega* **2018**, *3*, 14406–14416. [CrossRef]
207. Haghighi, M.; Abolghasemi, R.; da Silva, J.A.T. Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. *Sci. Hortic.* **2014**, *178*, 231–240.
208. Song, Y.; Jiang, M.; Zhang, H.; Li, R. Zinc oxide nanoparticles alleviate chilling stress in rice (*Oryza Sativa* L.) by regulating antioxidative system and chilling response transcription factors. *Molecules* **2021**, *26*, 2196.
209. Mustafa, G.; Sakata, K.; Hossain, Z.; Komatsu, S. Proteomic study on the effects of silver nanoparticles on soybean under flooding stress. *J. Proteom.* **2015**, *122*, 100–118. [CrossRef]
210. Tripathi, D.K.; Singh, S.; Singh, V.P.; Prasad, S.M.; Dubey, N.K.; Chauhan, D.K. Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (*Triticum aestivum*) seedlings. *Plant Physiol. Biochem.* **2017**, *110*, 70–81. [CrossRef]
211. Mahmoud, A.W.M.; Abdelaziz, S.M.; El-Mogy, M.M.; Abdeldaym, E.A. Effect of foliar ZnO and FeO nanoparticles application on growth and nutritional quality of red radish and assessment of their accumulation on human health. *Agriculture* **2019**, *65*, 16–29. [CrossRef]
212. Molnár, Á.; Papp, M.; Kovács, D.Z.; Bélteky, P.; Oláh, D.; Feigl, G.; Kolbert, Z. Nitro-oxidative signalling induced by chemically synthetized zinc oxide nanoparticles (ZnO NPs) in *Brassica* species. *Chemosphere* **2020**, *251*, 126419. [CrossRef]
213. Abdel Latef, A.A.H.; Srivastava, A.K.; El-sadek, M.S.A.; Kordrostami, M.; Tran, L.S.P. Titanium Dioxide Nanoparticles Improve Growth and Enhance Tolerance of Broad Bean Plants under Saline Soil Conditions. *Land Degrad. Dev.* **2018**, *29*, 1065–1073. [CrossRef]
214. Abbas, Q.; Liu, G.; Yousaf, B.; Ali, M.U.; Ullah, H.; Munir, M.A.M.; Rehman, A. Biochar-assisted transformation of engineered-cerium oxide nanoparticles: Effect on wheat growth, photosynthetic traits and cerium accumulation. *Ecotoxicol. Environ. Saf.* **2020**, *187*, 109845. [CrossRef]