

Review

Microalgae-Based Strategies for Soil Health and Crop Productivity: Mechanisms, Challenges, and Pathways to Climate-Resilient Agriculture

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Abstract

Microalgae hold significant potential as nature-based solutions in agriculture, offering benefits such as nitrogen fixation, enhanced nutrient cycling, stimulation of beneficial microbes, strengthening soil structure, and carbon sequestration. Yet, despite their potential, the role of microalgae, particularly through their interactions with soil systems, remains largely underexplored. Their ability to generate bioactive substances such as phytohormones, amino acids, and extracellular polymeric substances (EPS) fosters soil aggregation, nutrient availability, water retention, biological soil crust, and soil restoration, which ultimately supports plant growth and productivity. Moreover, the thermochemical conversion of microalgal biomass into biochar offers an effective strategy to improve carbon sequestration while simultaneously enriching soil nutrient content, thereby increasing crop productivity. While microalgae-based products often demonstrate strong efficacy under laboratory and greenhouse conditions, their performance in the field remains constrained by soil physicochemical properties, ecological incompatibility, competition with native microbial communities, and environmental variability, leading to inconsistent outcomes and highlighting the need for soil-specific, field-relevant strategies. Furthermore, the lack of standardized and cost-effective cultivation, formulation, and processing, along with low biomass yield and energy-intensive production, continues to limit their large-scale adoption in agricultural systems. Therefore, this narrative review aimed to discuss the mechanisms of coupling microalgal biomass and biochar to enhance soil health and crop growth, while also addressing field-performance constraints. It provides a balanced view of the potential and challenges of microalgae-based technologies for sustainable soil management and crop productivity. Overall, microalgae possess significant potential to improve soil health, increase crop yields, and contribute to sustainable agriculture that can withstand climate challenges.

Keywords: soil health; nitrogen fixation; carbon sequestration; soil microorganisms; sustainable agriculture



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1. Introduction

With the challenges of climate change and increasing worldwide food needs, sustainable farming has become more important than ever. Central to this initiative is soil, a frequently ignored but essential resource that sustains ecosystem functions, agricultural productivity, and mitigating climate change. Healthy soil, which serves as the basis of our food system, not only supports the growth of plants but also plays a role in conservation of biodiversity, nutrient cycling, water filtration, and carbon sequestration [1]. However, unsustainable farming management, overuse of chemical fertilizers, and the impact of climate change have led to severe soil degradation, including erosion, contamination, increased salinity, disrupted soil microbial communities, greenhouse gas (GHG) emissions, and nutrient imbalances [2,3].

Addressing these interlinked challenges requires innovative, nature-based, and eco-efficient solutions that restore soil health, improve crop productivity, and mitigate climate impacts. In this regard, microalgae biotechnology has emerged as a promising approach to achieve the United Nations 2030 Sustainable Development Goals by offering innovative solutions for sustainable agricultural practices and addressing climate change [4]. Microalgae, including cyanobacteria, consist of varied unicellular photosynthetic organisms that demonstrate remarkable photosynthetic efficiency, rapid growth, and adaptability, making them a sustainable agricultural resource [5]. They enhance soil fertility and resilience by fixing nitrogen, improving nutrient availability, cycling nutrients, sequestering carbon, and promoting beneficial microbes, while also supporting plant growth through bioactive compounds such as phytohormones, polysaccharides, amino acids, vitamins, and antimicrobial agents [6–8]. Moreover, they dominate soil crusts in arid and dryland ecosystems, stabilizing soil, enhancing nutrient availability, and supporting soil–plant interactions, which makes them valuable for ecological restoration and sustainable management of degraded lands [9–11].

Beyond their *in situ* ecological functions, they also generate valuable biomass for use as biofertilizers, biostimulants, and biochar. Microalgae-based biofertilizers and biostimulants enhance the biological, chemical, and physical characteristics of soil, while also encouraging plant development and nutrient cycling [12,13]. For instance, EPS secreted by microalgae aids in soil aggregation, increased carbon content, and foster the development of beneficial microbial communities that facilitate nutrient cycling [14]. Moreover, pyrolysis of algal biomass into biochar produces a stable, nutrient-rich material that enhances soil organic matter, nutrient retention, microbial diversity, and serves as a long-term carbon sink [15–17], thereby supporting sustainable agriculture and climate change mitigation.

The effectiveness of exogenous microalgae in agricultural soils remains inconsistent due to several key limitations. Their performance is highly context-dependent, influenced by soil physicochemical properties, native microbial communities, climatic conditions, and application methods [18,19]. Introduced microalgae may compete with native soil microorganisms for resources, reducing native populations or altering ecological niches [18,20]. Moreover, nutrient competition between introduced microalgae and resident soil microbes can hinder inoculum establishment and persistence, thereby reducing its effectiveness, especially in nutrient-deficient soils where competition is more intense [21]. This competition is one of the factors in why inoculants sometimes fail to persist and perform as expected.

Moreover, most strains are selected based on greenhouse and laboratory traits rather than ecological compatibility, limiting their persistence and functionality under diverse field conditions [22]. The ecological adaptation of numerous microalgal species to particular environments and specific physicochemical conditions restricts their ability to thrive and function optimally when placed in terrestrial or agricultural soils, creating a significant challenge in fully utilizing their potential as biofertilizers. A significant amount of microal-

gae biomass is essential for agricultural applications, particularly as growth enhancers and fertilizers. Their large-scale application still faces challenges, including inconsistent field performance, lower biomass production, high production costs, and limited long-term data, as much of the existing evidence comes from controlled greenhouse and laboratory studies [23,24]. In addition, the lack of standardized cultivation and formulation methods hinders the reproducibility and scalability of microalgae-based agricultural products.

We conducted a literature search of peer-reviewed studies across multiple databases with an emphasis on both controlled and field experiments. The review highlights how microalgae's biological mechanisms, bioactive compounds, and interactions with soil microbes and plants contribute to soil health and mitigate climate change, while also discussing associated limitations and challenges.

2. Microalgae: An Overview

Algae, the earliest photosynthesizing organisms on Earth, are classified based on size into macroalgae and microalgae. Macroalgae, commonly referred to as seaweed, are large, multicellular organisms that can be found in freshwater and marine environments. While microalgae are microscopic, unicellular eukaryotic organisms with high photosynthetic efficiency, belonging to diverse phyla such as Chlorophyta, Rhodophyta, Euglenophyta, and others. Functionally similar prokaryotic organisms, such as cyanobacteria, also contribute significantly to photosynthetic productivity and soil improvement [25,26]. Microalgae are among the most efficient carbon sinks, converting CO₂ into carbon-rich biomass. Microalgae form a diverse group with vast and largely untapped genetic potential, as currently known species account for only 1% of their estimated global diversity [27,28].

Microalgae can naturally thrive in both aquatic and soil environments. They can be cultivated under various systems, including open ponds, photobioreactors, or even efficiently cultivated using domestic or industrial wastewater [29]. Their rapid growth rate and ability to utilize sunlight, carbon dioxide, and inorganic nutrients make them highly efficient biomass producers. Microalgae, known as “living biorefineries,” can capture up to 1.8–2.0 kg of CO₂ per kilogram of biomass, making them a powerful tool for mitigating global warming [30,31].

In terrestrial and agricultural environments, microalgae and cyanobacteria in the soil are crucial for sustaining and improving soil fertility [32]. Utilizing native soil cyanobacteria in areas prone to erosion improves soil chemical characteristics such as nitrogen, organic matter, and carbon [33]. Microalgae also produce metabolites like superoxide dismutase, carotenoids, and proline, which help them survive drought stress and improve soil stability by enhancing its structural strength [34]. In dry conditions, microalgal filaments increase their surface area to absorb nutrients and prevent water loss [35].

Microalgae are used in several advanced agricultural applications, such as foliar application, seed coating or priming, and soil amendment. Microalgae, unlike conventional fertilizers, provide organic carbon to the soil, which is crucial for addressing soil organic carbon depletion and improving soil fertility [36,37]. It can be used in different forms in soil and plants: living biomass, dry biomass, and liquid leaf extracting compound [38]. The selection of technique is influenced by the type of crop, growth stage, and intended result, which may include promoting growth, increasing nutrient absorption, or stimulating soil microbial activity. Alongside increasing crop yields and enriching soil health, these products also provision the objectives of climate-smart agriculture by decreasing dependency on chemical inputs, lowering environmental impacts, and promoting the sustainability of farming systems [24,39].

Therefore, the beneficial effects of microalgae on soil functions and plant growth can be significantly improved and leveraged by applying algal biomass in various forms as

a biofertilizer, biostimulant, and algal biochar. Biofertilizers are products that contain natural substances or microorganisms that enhance soil properties, restore fertility, and improve crop productivity. Biostimulants are substances or microorganisms that enhance plant nutrition, improving nutrient use efficiency, stress tolerance, crop quality, or nutrient availability [40].

3. Mechanism of Soil Health Improvement by Microalgae

Microalgae and cyanobacteria are emerging as powerful tools for improving soil health and supporting sustainable agriculture. As shown in Figure 1, when applied as biostimulants or biofertilizers, their biomass provides a wide range of benefits, from enhancing nutrient availability to stimulating plant growth and resilience. For the purpose of this review, we categorized the different mechanisms into the following groups: nitrogen fixation, phosphorus solubilization, production of bioactive compounds, stimulation of microorganisms, and formation of biological soil crust. In addition, the decomposition of microalgal biomass contributes to a slow release of macro- and micronutrients [41,42], while biochar derived from microalgae serves as a valuable soil amendment, enhancing carbon sequestration and long-term fertility [43]. Through these interconnected mechanisms, microalgae enhance soil fertility, aggregation and structure, stimulate microbial activity, improve nutrient and water retention, reduce dependence on chemical fertilizers, and thereby contributing significantly to sustainable soil management. In the following section, each mechanism will be described in detail.

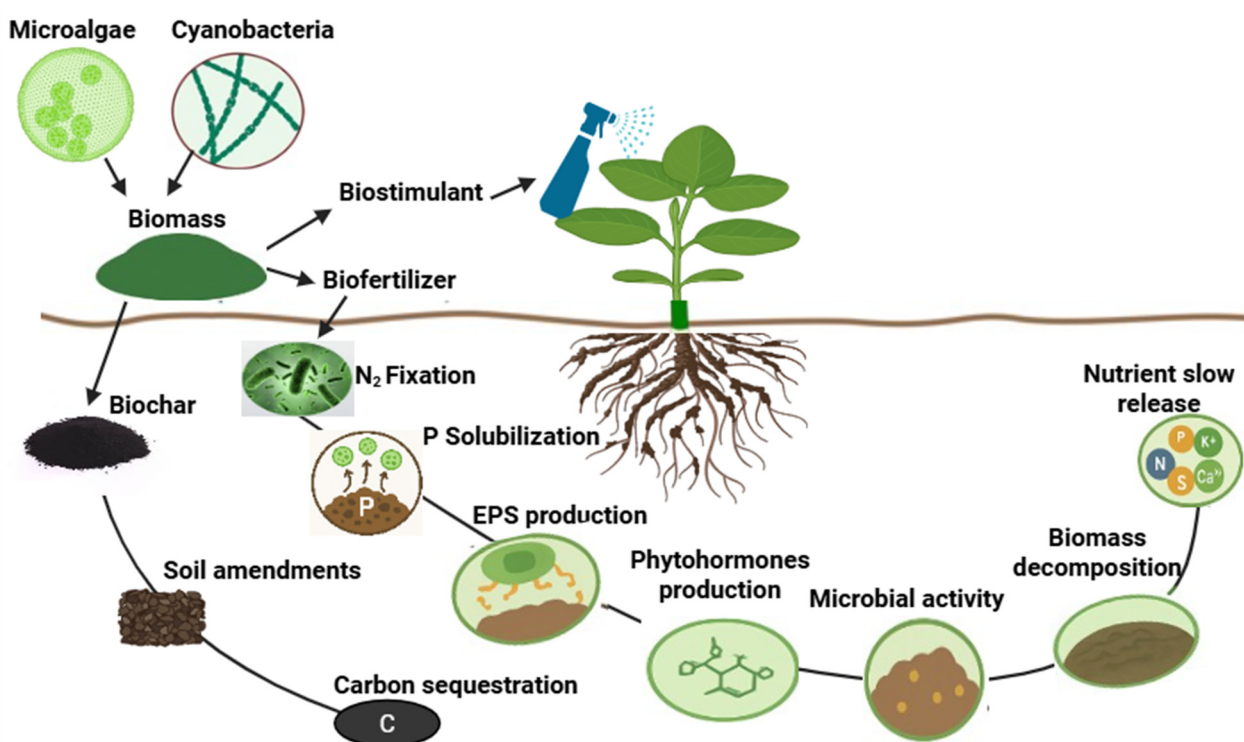


Figure 1. Schematic representation of the effects of microalgae and cyanobacteria-based products on soil and plants.

3.1. Nitrogen Fixation

Nitrogen constitutes 78% of Earth's atmosphere yet crops frequently experience nitrogen deficiency because atmospheric nitrogen (N₂) is stable and demands substantial energy for conversion into reactive nitrogen [44]. It is a vital nutrient for plant growth, playing a fundamental role in the synthesis of proteins, chlorophyll, and other essential compounds. Despite its importance, nitrogen in soils is often strongly unavailable to plants because

much of it is locked in organic forms or lost through leaching, volatilization, and denitrification [45]. To compensate for the limited availability of nitrogen in soils, conventional fertilization strategies primarily rely on synthetic chemicals, which raises concerns about their effects on environmental sustainability, soil health, and human well-being. As a more sustainable alternative, nitrogen fixation through biological means, such as by microalgae and cyanobacteria, can naturally enrich soils while supporting crop growth, ultimately reducing dependence on chemical nitrogen fertilizers [46,47].

Microalgae, including cyanobacteria, are essential to ecosystems by performing biological nitrogen fixation, a process that converts N_2 , which is unavailable to most organisms, into bioavailable forms such as ammonium (NH_4^+). This process, catalyzed by the nitrogenase enzyme complex, is energy-intensive and requires both ATP and a supply of electrons to reduce N_2 into ammonia (NH_3) and ammonium (NH_4^+) [48,49]. These processes are fundamental to nutrient cycling and primary production, highlighting their ecological and biogeochemical importance. Through this mechanism, microalgae supply essential nitrogen compounds that support their own growth as well as that of surrounding plants and microorganisms.

However, one significant obstacle in nitrogen fixation is the heightened sensitivity of nitrogenase to oxygen, which can restrict its functionality, especially in cyanobacteria where oxygenic photosynthesis produces elevated oxygen concentrations [50]. To overcome this, filamentous cyanobacteria develop heterocysts, which are specialized cells with thick walls that create an oxygen-free environment for nitrogen fixation, allowing them to convert atmospheric nitrogen into ammonium and organic nitrogen compounds [49]. The presence of nitrogenase in these cyanobacterial species gives them a competitive advantage in nitrogen-deficient environments, enhancing soil fertility and ecosystem productivity [51].

Beyond fixation, microalgae biomass contributes to mineralization after decomposition, releasing organic nitrogen in forms such as ammonium that can be assimilated by plants and soil microbes. Microalgae applied to soil act as biofertilizers, which enhance soil organic carbon levels, improving aeration, nutrient availability, structure, moisture retention, and support agricultural activity [12]. Biofertilizers are products that contain natural substances or living microorganisms capable of improving the biological and chemical properties of soil, restoring soil fertility, and crop productivity [52,53]. Applying live or dry microalgae as biofertilizers enhances crop development and increases yield potential [54]. This is achieved through their photosynthetic and nitrogen-fixing activities, which result in the mineralization and mobilization of both inorganic and organic nutrients.

Table 1 highlights the potential impact of microalgae-based biofertilizers on soil fertility and their role as sustainable supplement to synthetic fertilizers. Microalgal extracts enhance the availability of key macronutrients, including calcium, magnesium, potassium, and phosphorus, [41]. Typically, the choice of microalgae as biofertilizers is generally determined by their capacity to fix atmospheric nitrogen and promote plant growth through various beneficial actions. Algae-based fertilizers, including *Nostoc* sp., *Chlorella vulgaris*, *Anabaena azolla*, *Scenedesmus dimorphus*, and *Spirulina platensis*, have been effectively utilized to boost crop growth and soil health [36,55]. Further, microalgae treatments such as *Scenedesmus quadricauda*, *C. vulgaris*, and *Klebsormidium* sp., especially when combined with mineral fertilizers, significantly enhanced crop growth, yield, protein content, and soil enzymatic activities, while reducing nitrate leaching, indicating their potential as a sustainable strategy to recover soil fertility and lessen reliance on chemical fertilizers [56–58].

Table 1. Effects of microalgae-based biofertilizers on soil fertility and plant growth.

Microalgae/Cyanobacteria Species	Baseline Soil Properties	Experimental Condition	Impacts on Soil/Plant	References
<i>Desmodesmus</i> sp. and <i>Heterochlorella</i> sp.	Acid soil	Soil incubation using Petri dishes	Significantly improved soil health by increasing pH (~1 unit), carbon content (29–57%), exopolysaccharides (>200%), dehydrogenase activity (>500%), and indole acetic acid production (200–500%).	[59]
<i>Chlorella minutissima</i>	Low organic carbon	Field plots with spinach (<i>S. oleracea</i>) and maize (<i>Z. mays</i>)	Reduced soil nitrate leaching and enhanced soil organic carbon, microbial activity, plant growth, and yield.	[60]
<i>Anabaena</i> sp.	Limited availability of micronutrients	Pot experiment under net house conditions with okra (<i>Abelmoschus esculentus</i>)	Enhanced soil iron concentration by 2–3 times and boost microbial carbon biomass	[61]
<i>Chlorella sorokiniana</i>	Low nutrient levels	Laboratory germination assay and pot experiment in a climatic chamber with wheat (<i>Triticum aestivum</i>)	Enhanced nutrient excretion and extracellular substances. Aboveground and belowground biomass increased by 22% and 55%, respectively.	[62]
<i>Chlorella vulgaris</i> and <i>Spirulina platensis</i>	Low nitrogen and potassium	Greenhouse condition with maize (<i>Z. mays</i> L.)	Improved soil fertility, enhanced early-stage growth, and promoted yield-related traits.	[63]
<i>Anabaena</i> – <i>Pseudomonas</i> biofilm	Low available nitrogen and organic carbon	Pot experiment under controlled conditions with wheat (<i>Triticum aestivum</i>)	Improved nitrogen fixation ability, enhanced P uptake, and increased growth and nutrient absorption	[64]
<i>Nostoc calcicola</i> BOT1, <i>Scytonema</i> sp. BOT2	Nutrient and water deficient soil	Laboratory microcosm experiment in Petri plates with rice (<i>Oryza sativa</i>)	Significantly improved soil fertility, promoted biocrust formation, and stimulated plant growth. It supports degraded land rehabilitation and persist in soil after prolonged desiccation.	[65]
<i>Chlorella</i> sp. and <i>Scenedesmus</i> sp.	Low organic carbon and available nitrogen	Pot experiments under controlled growth cabinet and greenhouse conditions with spinach (<i>Spinacia oleracea</i> L.)	Increased microbial diversity, slowed nitrogen release, improved foliage greenness, and enhanced soil water retention.	[57]
<i>Chlorella vulgaris</i> and <i>Spirulina platensis</i>	Low phosphorus and organic matter content, with alkaline soil.	Field experiment with rice (<i>Oryza sativa</i>)	Enhanced soil nitrogen levels, enzyme activity and increased rice yield up to 7–20.9%.	[66]
<i>Nostoc</i> sp.	Poor soil aggregation	Soil inoculation	Enhanced soil aggregation	[67]
<i>Chlorella vulgaris</i>	Low organic matter and carbon	Pot experiment in a greenhouse with tomato (<i>Solanum lycopersicum</i>)	Increased fruit length, diameter, weight, and seed number, enhanced fruit mineral content (P, Ca, K, Mg), and extended fruit shelf life.	[41]

While amendments derived from microalgae have been promoted for their ability to improve soil fertility and increase crop yields, there is also evidence indicating situations where unintended adverse outcomes that deserve careful consideration. For instance, in a sandy soil pot experiment the incorporation of *C. vulgaris* enhanced nutrient availability (notably N, P, and Ca) and reduced nutrient leaching, yet simultaneously increased sulfate (SO_4^{2-}) concentrations in soil leachates, posing a groundwater pollution risk [68]. In another study, application of *C. vulgaris* biomass increased soil NH_4^+ and NO_3^- in soil pools, but crop uptake was low (0.7% of added N), with 10% retained in the soil after 30 days [69], this show that some nitrogen was lost or unavailable due to immobilization in soil or microbial biomass. Moreover, under conditions of high organic C and low O_2 (e.g., coarse-textured soils, limited aeration), decomposition of algal biomass can accelerate denitrification: for instance, one investigation documented a 7 mm reduction in O_2 penetration and enhanced $\text{NO}_3^-/\text{NO}_2^-$ fluxes in the sediment–water interface [70]. This risks may arise in soils when algal amendments alter C:N dynamics and oxygen availability, thereby intensifying denitrification or transient nitrogen immobilization. These findings highlight the trade-offs inherent in algal amendments, improved nutrient retention on one side, but risks of sulfate mobilization, nitrogen immobilization or gaseous loss on the other.

Shrestha et al. [71] evaluated the effects of applying microalgal biomass (*Coelastrella* sp.) as fertilizer on wheat grown in a field experiment, compared to conventional urea fertilization. Microalgae application had minimal effect on aboveground biomass but slightly reduced wheat grain nitrogen content. Importantly, soil emissions of nitric oxide (NO) and nitrous oxide (N_2O) were substantially lower, with NO reduced 2–5 fold and N_2O reduced approximately 2-fold. However, considering the CO_2 emissions from algae cultivation, the overall climate impact was similar to or up to 40% higher than urea. These results indicate that microalgae can reduce soil nitrogen losses and greenhouse gas emissions, but the carbon footprint of biomass production must be considered when evaluating its environmental benefits.

Moreover, recent research has explored different forms of algae amendment can alter N cycling and possibly increase losses if conditions favor denitrification. The study by [72] investigated how different microalgae processing methods influence soil nitrogen cycling. The results demonstrated that wet microalgae amendments are more effective in enhancing nitrogen retention by promoting dissimilatory nitrate reduction to ammonium (DNRA), which minimizes nitrogen losses typically associated with denitrification and nitrification. In contrast, drying or dewatering microalgae appears to be less effective for fertilizer production, as wet microalgae exhibit higher potential to boost DNRA activity and retain nitrogen in soils. To maximize the efficiency of microalgae-based fertilizers, future research should explore the optimization of application methods, appropriate concentrations, species selection, and timing.

3.2. Phosphorus Solubilization

Phosphorus (P) is an essential but immobile soil nutrient, often limiting crop productivity due to its low availability to plants. Although the concentrations of plant available phosphorus in soil solutions are typically lower than the amounts needed by plants, the deficiency of phosphorus in agriculture is addressed through significant applications of P fertilizers [73]. However, this practice is inefficient, as crops typically take up less than 20% of the applied phosphorus during the growing season [74]. The remaining phosphorus contributes to environmental degradation, particularly through runoff that contaminates water bodies [75]. Enhancing its availability through the use of phosphate-solubilizing microorganisms (PSMs) offers a sustainable solution to improve soil–plant phosphorus dynamics [76]. PSMs mobilize insoluble phosphorus by using mechanisms such as acid-

ification, chelation, enzymatic cleavage, ion exchange, and the secretion of polymeric substances. These processes not only increase plant-accessible phosphorus but also contribute significantly to biogeochemical phosphorus cycling and nutrient sustainability in agricultural practices [77].

Microalgae and cyanobacteria enhance soil health by boosting phosphorus accessibility for plants, which may decrease the reliance on chemical fertilizers. Cyanobacteria and microalgae, as key PSM, play a vital role in making phosphorus available to plants by mobilizing phosphorus bound to calcium in alkaline soils or to aluminum in acidic soils, depending on the soil pH [24]. Cyanobacteria release bound phosphorus through two mechanisms: either by producing chelating agents that bind to calcium ions or by excreting organic acids that facilitate solubilization [25]. Yandigeri et al. [78] demonstrated that the cyanobacteria *Westiellopsis prolifica* and *A. variabilis* can solubilise Ca-bound mineral phosphates by producing aromatic chelating compounds (phthalic acid) rather than classical low-molecular-weight organic acids. Moreover, Afkairin et al. [77] demonstrated that *Anabaena* sp. markedly enhanced the solubilization of organic phosphorus sources in alkaline soil through elevated phosphatase activity.

Moreover, beyond inorganic P solubilization, microalgae also play a vital role in P mineralization by breaking down organic P compounds, contributing to plant-available P and enhancing soil P cycling. This is achieved through the production of extracellular enzymes like phosphodiesterases, alkaline phosphatases, and phytases, which hydrolyze various organic P forms like phosphoesters, phosphodiesteres, and phytic acid [79,80]. For instance, *Euglena gracilis* [80] and *Chlamydomonas reinhardtii* [81] have shown phytase activity, enabling them to release inorganic P from phytate in both aquatic and soil environments. Additionally, when microalgal biomass is added to the soil, decomposition of its organic matter releases nutrients, further contributing to the pool of plant-available phosphorus [82]. This dual role, active enzymatic mineralization of organic P and passive release through biomass degradation, makes microalgae promising agents for enhancing phosphorus availability in sustainable agricultural systems.

Most microorganisms, including microalgae, employ various adaptive strategies to cope with phosphorus scarcity, including the ability to store excess phosphorus when it is abundantly available. Microalgae exhibit a luxury P uptake mechanism, where excess P from the environment is stored intracellularly as polyphosphate (polyP) granules for later use under P-deficient conditions [83,84]. PolyP is crucial for providing the necessary components for DNA synthesis throughout the cell division cycle and is also plays a role in nitrogen fixation and the storage of nutrients [85]. This luxury uptake and internal storage of phosphorus is enhanced by membrane lipid remodeling, allowing these organisms to reallocate internal P by replacing phospholipids with non-P-containing lipids such as glycolipids and betaine lipids during P starvation [86]. Such adaptive responses, reported in fast-growing and high P-accumulating species like *Nannochloropsis salina* [87], *Synechocystis* sp. [88], and *Nannochloropsis gaditana* [89], not only support microalgal survival under nutrient stress but also present potential for mobilizing and delivering soluble P to plants in agricultural systems.

3.3. Production of Bioactive Compounds

Microalgae produce a wide array of biologically active compounds, including phytohormones, amino acids, polysaccharides, polypeptides, vitamins, antimicrobial agents, and EPS. These compounds collectively enhance soil quality, stimulate microbial interactions, and support plant growth by improving nutrient availability, soil structure, and water retention [24,30,90].

These microorganisms synthesize a variety of phytohormones such as auxins, cytokinins, gibberellins, and abscisic acid, which regulate plant physiological and biochemical processes, including cell division, elongation, and stress responses [91]. Phytohormones are natural chemical signals that control plant growth and development, enhance nutrient absorption, initiate seed germination, and promote the growth of roots and shoots. They also assist plants in managing stress by increasing antioxidant defenses and enhancing the efficiency of nutrient and water use [92,93]. Further, their positive effects on plant growth are attributed to their ability to improve critical processes like photosynthesis, nucleic acid synthesis, ion absorption, and respiration, ultimately boosting overall plant metabolism [94–96].

Phytohormones act as natural biostimulants by encouraging plant development, boosting nutrient absorption, increasing resilience to stress, and stimulating beneficial soil microbial activity [97–99]. Biostimulants are characterized by their ability to improve the processes of plant nutrition, independent of their nutrient composition, with the goal of enhancing nutrient utilization efficiency, resilience to stress, crop quality, or the availability of nutrients in the rhizospheres [100]. Their application enhances agricultural yield, optimizes nutrient use efficiency, and strengthens plants' ability to withstand environmental challenges like drought, salinity, extremes temperature, and heavy metal contamination [101]. The specific constituents of each microalgal biostimulant determines mode of action, as each bioactive compound can trigger unique biological responses in plants [102].

Table 2 highlights the biostimulant properties of phytohormones and other bioactive compounds produced by various microalgae and cyanobacteria species, demonstrating their capacity to enhance plant growth and development. For instance, cyanobacteria like *Nostoc* and *Anabaena* are known to produce auxins, which stimulate root development and improve nutrient uptake in plants [103]. Similarly, microalgae-derived cytokinins enhance shoot growth and delay senescence, contributing to increased crop productivity. In addition, these bioactive compounds strengthen plant–microbe interactions, supporting a more robust and healthy soil ecosystem [37]. Moreover, application of *S. platensis*, either as powder or extract, significantly enhanced sesame growth, antioxidant activity, yield traits, and mineral composition, demonstrating their potential as effective bio-stimulants and sustainable alternatives to chemical fertilizers [104].

Table 2. Effects of the microalgae-based biostimulants on crop growth and development.

Microalgae/Cyanobacteria Species	Bioactive Compounds	Experimental Condition	Impacts on Crop Performance	References
<i>Nostoc calcicole</i> ; <i>Anabaena vaginicola</i>	Auxins (IAA)	Pot experiments with wheat (<i>Triticum aestivum</i>) using spraying algal extracts	Significant improvement in plant height, root length, and biomass.	[105]
<i>Chlorococcum</i> , <i>Micractinium</i> , <i>Scenedesmus</i> , and <i>Chlorella</i>	Cytokinins, gibberellins, auxin (IAA) and abscisic acid	Greenhouse with spinach (<i>Spinacia oleracea</i> L.) seeds were primed	Achieved a 1.7-fold increase in seed germination and up to a 2.1-fold increase in seedling biomass.	[106]
<i>Anabaena vaginicola</i> and <i>Nostoc calcicola</i>	Auxins (IAA and Indole-3-butyric acid (IBA))	Greenhouse pot experiment with tomato, cucumber, and squash were conducted by spraying algal extract	Notable increases in plant height, fresh and dry weight, and root length.	[107]

Table 2. Cont.

Microalgae/Cyanobacteria Species	Bioactive Compounds	Experimental Condition	Impacts on Crop Performance	References
<i>Chlorella</i> sp. and <i>Chlamydomonas reinhardtii</i> cc 124	Auxin (IAA)	Greenhouse pot experiment with tomato (<i>Solanum lycopersicum</i>) treated by algae extract	Enhanced pigment levels were observed, along with increased fruit weight and diameter.	[108]
<i>Chlorella vulgaris</i>	Auxin (IAA)	<i>Arabidopsis thaliana</i> was treated with algae extract	Root and shoot growth, along with drought tolerance, were substantially enhanced.	[109]
<i>Scenedesmus</i> sp.	Cytokinins, auxins (indoleacetic acid)	Greenhouse pot experiment with <i>Petunia x hybrida</i> were conducted by foliar spray	Shoot, leaf, and flower growth, along with plant nutrient status, were enhanced.	[110]
<i>Chlamydomonas</i> sp., <i>Chlorella</i> sp. and <i>Desmodesmus</i> sp.	Exopolysaccharides	Controlled chamber and greenhouse with rice (<i>Oryza sativa</i> L.) were conducted by seed inoculation and foliar application	Increased root dry weight by 43%, shoot dry weight by 36%, and number of seeds by 11%.	[111]
<i>Chlorella</i> sp. and <i>Chlamydomonas reinhardtii</i>	Exopolysaccharides	Greenhouse conditions with <i>medicago truncatula</i>	Enhanced biomass, pigment levels (chlorophylls and carotenoids), and flower count.	[112]

Microalgae, rich in amino acids, serve as effective biostimulants in promoting plant growth and improving soil health [96]. These amino acids, such as glutamic acid, aspartic acid, and arginine, act as signaling molecules and precursors for proteins and other growth-regulating compounds. The use of microalgal or macroalgal extracts enriched with specific amino acids as biostimulants has been shown to induce various physicochemical changes in plants, stimulating the production of proteins, pigments, and key growth-regulating compounds that enhance plant growth [93,113]. For instance, root application of *Spirulina platensis* optimized biomass production in papaya seedlings [113], while foliar applications of *A. vaginicola* and *N. calcicola* significantly improved growth parameters in cucumber, tomato, and squash [107]. They enhance nutrient absorption, promote root growth, and increase plants' resilience to stress, all while encouraging positive microbial activity in the soil [114].

Amino acids derived from microalgae contribute to sustainable farming by reducing dependence on synthetic fertilizers and enhancing overall soil health. Microalgae, unlike conventional fertilizers, provide organic carbon (C) to the soil, which is crucial for addressing soil organic C depletion and improving soil fertility [36,37]. Additionally, they are known for their broad environmental adaptability and hold potential for rehabilitating degraded soils, including desertified and saline-alkali lands [26,115].

EPSs, which are intricate high-molecular-weight polymers generated by microalgae, play a crucial role in supporting their life processes and interactions with the environment while also greatly improving soil structure and promoting microbial activity [116]. Microalgal EPS mainly consist of polysaccharides, proteins, lipids, and nucleic acids [117,118]. EPS is also produced by many microalgae and cyanobacteria, especially under diverse biotic and abiotic stress conditions [119]. These molecules form a protective, moisture-retaining layer around cells that shields them from environmental stress, promotes soil particle aggregation, and aids plants by conserving moisture and trapping essential nutrients [90,120].

EPS function as natural facilitators, improving soil health by fostering soil aggregation, enhancing water retention, and establishing suitable microhabitats for beneficial microorganisms [14,121]. Certain microalgae species exhibit substantial increases in extracellular and intracellular polysaccharides during growth, contributing to higher soil carbon fixation and enhancing both total carbon and dissolved organic carbon levels [122]. Microalgae-derived EPS are recognized for their capability in bioremediation, essentially in the remediation of heavy metals [123]. Studies shows that EPS produced by microalgae under mixotrophic conditions enhance biosorption of environmental contaminants, with modified biochemical composition and functional groups, particularly from *C. vulgaris*, showing strong potential for Pb(II) removal [124]. This metal-sequestering capacity is particularly valuable for improving soil quality in agricultural areas and for pretreating metal-contaminated wastewater used in irrigation.

By strengthening soil aggregation, EPS supports healthier soil ecosystems, promotes plant growth, and helps alleviate the impacts of environmental challenges like drought and intense rainfall. During cell decomposition, the production of EPSs by microalgae enhances soil organic carbon levels, providing an accessible carbon source that supports the growth of soil microbiota, particularly under climate change conditions [125].

3.4. Stimulation of Soil Microbial Interactions

Microbial communities, such as bacteria, fungi, microalgae, actinomycetes, and viruses, are indispensable to the plant–soil ecosystem, ensuring long-term sustainability. These microorganisms are fundamental to breaking down organic matter, sequestering carbon, and transforming nutrients through mechanism like oxidation, nitrification, and nitrogen fixation [48]. Microalgae stimulate soil microbiota through multiple interlinked mechanisms that enhance soil fertility and ecological resilience.

Through their photosynthetic activity, microalgae produce EPS, organic acids, and bioactive compounds that not only enrich microbial habitats but also create synergistic interactions among bacteria, fungi, and other soil biota [25]. Particularly, interactions within microalgae–bacteria consortia can be either synergistic or competitive, depending on nutrient availability and environmental conditions. Synergistic relationships occur when microalgae releases dissolved organic carbon and release oxygen into their surrounding microenvironment that stimulate bacterial activity, such as nitrogen fixation, nitrification, and organic matter decomposition. In return, associated nitrogen-fixing and phosphate-solubilizing bacteria releases nutrients, including nitrogen, phosphorus, carbon dioxide, and growth promoters that support algal growth and overall soil fertility [126–128]. For instance, the combined use of cyanobacteria (*N. linckia*) and *A. lipoferum* led to a notable increase in soil fertility, with total nitrogen rising by 20.7% to 40% and nitrate plus nitrite nitrogen increasing by 27.1% to 59.2% relative to uninoculated soils [129]. This indicates that the collaboration between microalgae and bacteria effectively enhances nutrient cycling in the soil, especially concerning nitrogen dynamics, which in turn supports crop growth and promotes soil health. Conversely, competitive interactions can arise in situations where nutrients are limited, especially in soils lacking phosphorus, as both microalgae and bacteria compete for scarce resources, which may lead to decreased nutrient uptake efficiency and microbial stability [130]. These consortia bolster nutrient availability, support biomass production, and have promising biotechnological value [131].

Importantly, by supporting a diverse array of microbial groups, microalgae foster soil biodiversity, an essential measure of soil health and its ability to withstand climate stress [132]. Soil biodiversity enhances functional redundancy, ensuring that critical processes such as nutrient cycling, organic matter decomposition, and disease suppression remain stable even under disturbance [133]. The combination of nutrient complementarity

and stimulation of microbes leads to improved nutrient cycling, better interactions between roots and microbes, and a more robust rhizosphere, thereby supporting improved plant growth and soil quality [18]. The diversity within microalgae–microorganism symbiotic systems boost soil health by enhancing ecosystem stability, raising crop resistance to environmental challenges, such as salinity [18,134].

Microalgae-based fertilizers can significantly change the microbial community in the soil by promoting the development of beneficial microbial populations while simultaneously restricting the presence of detrimental ones. In particular, studies have indicated that their use boosts the numbers of helpful bacteria and fungi such as *Thermaerobaculia*, *Microascaceae*, and *Sordariomycetes*, while decreasing the levels of plant pathogens like *Pseudomonas*, *Togniniaceae*, and *Phaeoacremonium* [135]. This shift may be due to a variety of interacting processes. It is widely recognized that microalgae produce EPS and easily degradable organic carbon during their growth and when they are applied to soils, which increase the soil carbon content and promote the presence of saprophytic and symbiotic microorganisms. Additionally, the synthesis of phytohormones and antimicrobial compounds can boost root growth and inhibit the proliferation of pathogens. These processes work together to enhance the presence of beneficial microbial groups while diminishing pathogens, thus improving soil health, increasing disease resistance, and supporting a more robust and productive agricultural ecosystem. Employing biofertilizers derived from active microalgae can enhance soil microbial ecosystems, nutrient use efficiency, abiotic stress tolerance, and minimize dependence on fertilizers [36,48].

3.5. Microalgae in Biological Soil Crusts: Their Importance in Dryland Ecosystem and Soil Restoration

Dry and semi-dry regions cover 41% of the world's land surface and sustain over 38% of the entire human population [136] and face significant anthropogenic degradation that leads to the loss of ecosystem integrity and services, as well as the deterioration of social-ecological systems. In the early stages of primary succession in arid and dryland ecosystems, plant cover is sparse, and growth conditions are stressful, allowing poikilohydric cryptogams, particularly autotrophic cyanobacteria and green algae, to act as first colonizers and form biological soil crusts (BSC) [137]. BSCs are essential for dryland ecosystems, enhancing soil stability and fertility by binding soil particles to prevent erosion, improving water retention, and contributing to carbon storage through complex microbial networks [138]. Biocrusts, which are intricate assemblages of algae, fungi, lichens, and bryophytes, play a crucial role in soil stabilization, erosion prevention, and nutrient cycling facilitation [139].

Microalgal and cyanobacteria biocrusts are crucial components of dryland ecosystems, thriving even in harsh desert environments and serving as ecosystem engineers [140]. In many dryland ecosystems, particularly where the coverage of vascular plants is low, biocrusts can account for over 40% of soil surface cover, and in some localized areas, coverage exceeds 70%, particularly in interpatch zones dominated by cyanobacteria and lichens [141,142]. The structure, species composition, and thickness of BSCs, ranging from less than 1 mm in newly established crusts to 1–5 mm in more developed cyanobacterial/green-algae crusts [9], are largely influenced by abiotic factors such as surface wetness duration, and these crusts can later be succeeded by moss and lichen dominated stages in semiarid to humid regions [143].

EPSs produced by microalgae, especially cyanobacteria, are integral to soil stabilization by facilitating the formation of biological soil crusts [144]. By releasing EPS, as well as engaging in photosynthetic carbon–nitrogen fixation, they profoundly change the physico-chemical attributes of the soil, which in turn influences hydrological features and improves resistance to erosion [140]. Cyanobacteria act as ecological engineers by improving soil

structure and aggregate stability, facilitating ecological processes, and providing habitats for diverse organism [103]. In desert soil crusts, these microorganisms enhance desiccation tolerance by adjusting carbohydrate metabolism, particularly increasing EPS and sucrose production, to mitigate reactive oxygen species accumulation and oxidative damage in arid regions [145]. The extent of EPS promote soil aggregation is influenced by soil structure and texture, microbial community, and root exudation [146]. According to the study, EPS-R1 produced by *Paenibacillus tarimensis* significantly increased soil aggregation, stability, and permeability in calcareous, silty-clay saline soil. It decreased disintegration, increased permeability by 251%, and produced up to 86.9% macroaggregates (>2 mm), demonstrating its potential as a bio-structuring amendment, especially for arid and degraded soils [147]. However, when EPS build up excessively, it can cause bioclogging, which partially blocks pore spaces and drastically lowers hydraulic conductivity and porosity in the soil matrix [148,149]. Because EPS can more easily obstruct the small pore networks of fine-textured soils like clays, bioclogging is more common in these types of soils and causes a faster decline in hydraulic conductivity [150]. In order to prevent excessively compacted or tight aggregate structures, it is advised to use organic amendments, such as straw, when using EPS, particularly in clay soil. These amendments are known to increase porosity, lower bulk density, and improve structural resilience.

Studies show that inoculating cyanobacterial species, *Scytonema javanicum* and *Phormidium ambiguum*, in different soil types led to the formation of biocrusts, with *P. ambiguum* enhancing exopolysaccharide content and soil resistance, while *S. javanicum* increased organic C and N content, both improving soil aggregation through their filaments and extracellular secretions [11]. These biological soil crusts provide a variety of ecosystem benefits, including controlling soil erosion, improving the availability of nutrients and water, facilitating soil development, and recycling nitrogen and carbon. In cold climates, their slow degradation rates increase soil organic carbon, thereby contributing to carbon sequestration and positioning these soils as important carbon sinks [151]. Beyond carbon sequestration, the breakdown of EPS releases organic matter into the environment, fueling microbial activity and nutrient cycling [120].

BSCs play critical ecological roles by stabilizing the soil surface, regulating hydrological processes including infiltration, runoff, and evaporation, and supplying carbon and nitrogen to the ecosystem, thereby influencing vegetation patterns and overall soil–plant interactions [140,152,153]. It also plays a crucial role in influencing soil structure and surface morphology, as well as in capturing and retaining organic matter and essential resources, ultimately enhancing soil fertility through their impact on atmospheric carbon and nitrogen fixation [65].

4. Microalgae-Derived Biochar or Hydrochar for Soil Health

The growing algae-based industry addresses concerns over algal waste management by converting residues into functional biochar, mitigating ecological impacts and enhancing commercial sustainability [154]. Biochar, a carbon-rich material produced from plant- or animal-based biomass through thermal conversion under limited oxygen conditions, has obtained considerable attention for its ability to address critical global challenges, like soil degradation, climate change, and environmental pollution [155]. Common thermochemical conversion methods for biochar production include pyrolysis, hydrothermal carbonization (HTC), torrefaction, and gasification [156]. Hydrochar is produced through hydrothermal carbonization (HTC), which converts wet biomass into a stable, carbon-rich material under high heat and pressure in an aqueous environment. The HTC process usually functions at temperatures between 180 and 250 °C and pressures of 2–6 MPa, which makes it especially

efficient for handling feedstocks with high moisture content such as food waste, agricultural residues, and algae [157].

Microalgae, with their inherent carbon sequestration potential driven by photosynthesis, can be further valorized by pyrolyzing them into biochar. This transformation not only locks atmospheric carbon into a stable form but also creates a long-lasting soil amendment that improves both fertility and sustainability. The rich composition of carbohydrates, lipids, proteins, nucleic acids, and unsaturated fatty acids in both macroalgae and microalgae contributes to the production of high-quality biochar, with its physical and chemical properties determining its overall quality [158]. Moreover, algae, rich in protein, tend to produce biochars with a greater concentration of nitrogen-rich compounds like amide, amine, phenols, pyrrole, carboxylic acids, pyridine and other compounds, making them ideal for soil enhancement and environmental remediation [159–161]. Such nitrogen-enriched biochars can improve soil microbial activity, support crop growth under nutrient-limited conditions, and aid in the immobilization of heavy metals and pollutants.

Microalgal biochar, produced under low temperatures and limited oxygen conditions, resulting in a carbon-rich material with a nutrient-dense profile and strong ion-exchange properties [16,162]. This form of biochar is widely regarded for its role in enhancing soil health and efficiently adsorbing pollutants from air and wastewater. Additionally, low-temperature torrefaction during pyrolysis converts algal biomass into coal-like fuel, demonstrating the versatility of algae-derived biochar across a range of applications. In contrast, high-temperature carbonization of algal biochar produces materials with a graphitic carbon framework, excellent electron conductivity, and a substantial surface area, making them ideal for applications such as supercapacitors, CO₂ adsorption, and persulfate activation [154].

The study by [43] investigated the pyrolysis of three microalgae species (*C. vulgaris*, *Nannochloropsis* sp., and *Spirulina* sp.) using thermogravimetric analysis. The results revealed that microalgae-derived biochar contains ten times more nitrogen and phosphorus than plant-based materials like wood or crop residues, along with more oxygen-rich surface groups, highlighting its significant potential for environmental applications. Moreover, the cultivation of *C. vulgaris* in photobioreactors with varying CO₂ concentrations resulted in high biomass productivity, and pyrolysis at 500 °C produced biochar with favorable properties for carbon sequestration and bio-adsorption, highlighting its potential as a sustainable technology for carbon capture and microalgal biorefinery [16]. Moreover, *Scenedesmus* sp. biochar produced via HTC was repurposed as a biofertilizer. When biochar applied to tomato plants, the biochar increased plant height to 22 cm (compared to 10 cm in controls), chlorophyll content to 24.5 mg/g (versus 10.4 mg/g in controls), and dry weight to 640 mg (versus 285 mg in controls), demonstrating its potential as a sustainable fertilizer [163].

Table 3 shows that microalgae-derived biochar, when used as a soil amendment, enhances crop growth and quality while significantly improving long-term carbon storage and soil fertility. It acts as an eco-friendly substitute for chemical fertilizers, enriching soil nutrients, boosting crop productivity, and improving soil quality by enhancing water retention, increasing soil permeability, and facilitating the gradual release of nutrients [17,164]. Additionally, its stable structure and strong carbon retention capacity make it an efficient agent for carbon sequestration [165]. These properties collectively improve nutrient availability, strengthen water retention, and enrich soil health, resulting in higher agricultural output.

Table 3. Effects of microalgae-based biochar and hydrochar on agricultural applications.

Microalgae/Cyanobacteria Species	Product and Produced Methods	Chemical Properties of the Product	Soil/Plant Evaluation	Effects on Soil/Plant	References
<i>Arthrospira platensis</i>	Biochar (produced slow pyrolysis at 300 °C)	C-51% N-26% O-20%	Rice (<i>Oryza sativa</i>)	Significantly increased seeds per plant, seed weight, root dry weight, and grain yield.	[166]
<i>Chlorella vulgaris</i> and <i>Microcystis</i> sp.	Hydrochar (HTC at 200 °C)	C-60.5% H-3.3% N-8.1% pH-6.1	Wheat (<i>Triticum aestivum</i> L)	Increased soil available P, improved plant P use efficiency by 34.4%, and enhanced wheat yield by 21.6%.	[167]
<i>Spirulina platensis</i>	Biochar (pyrolysis at 400 °C)	C-59.68% N-10.36% H-3.93%	Soil	Reduced lead (Pb) and zinc (Zn) contamination in soil.	[168]
<i>Spirulina dimorphus</i>	Biochar (Pyrolysis at 600 °C)	C-53.58% N-6.5% H-8.5%	Soil	Increased soil fertility and carbon sequestration.	[169]
<i>Arthrospira platensis</i>	Hydrochar (HTC at 210 °C)	C-68.3% H-8.5% N-6.7%	-	Improved nitrogen use efficiency and biomass yield, while reducing the need for chemical nitrogen fertilizers by 60%.	[170]
<i>Cladophora vagabunda</i>	Biochar (Pyrolysis at 400 °C)	C-29.5% H-3.53% N-6.55%	Sorghum (<i>Sorghum bicolor</i>)	The relatively high nutrient content improved soil amendment value and demonstrated potential for long-term carbon sequestration.	[171]
Specific species unknown	Biochar (Pyrolysis at 350 °C)	C-59.1% P-7.37 ppm K-14 ppm	Vigna radiata (Moong) and Pennisetum glaucum (Bajra)	Enhanced shoot growth, reaching 25.53 cm in Moong and 16.75 cm in Bajra, while also significantly improving plant yield and soil health.	[172]
<i>Oedogonium</i>	Biochar (Pyrolysis at 750 °C)	C- 30.7% H- 0.7% N- 3.0% pH-9.4	Stockpiled soils (ferrosol and sodosol)	Improved the establishment and growth of Kangaroo grass (<i>Themeda australis</i>) across both soil types, contributing to enhanced soil rehabilitation.	[173]
<i>Oedogonium</i>	Biochar (Pyrolysis at 750 °C)	pH-10.03 EC-254 ($\mu\text{S cm}^{-1}$)	Radishes (<i>Raphanus sativus</i>)	Improved radish growth by 35–40%, higher nutrients content of crop (Mo, Mg, Ca, P, K), and lower metal content, and enhanced soil quality.	[174]

5. Microalgae for Soil Health and Climate Resilient Agriculture

Climate change significantly affects soil health and crop productivity by exacerbating abiotic stresses, including drought, salinity, extreme temperatures, and nutrient deficiencies, while also intensifying biotic pressures from pathogens and pests [175]. These interconnected challenges threaten agricultural sustainability by reducing soil fertility, reduce organic matter, disturb microbial community, impairing plant growth, and diminishing overall crop yields. Conventional farming practices that depend extensively on synthetic fertilizers and unsustainable soil management contribute to the rapid soil degradation, nutrient leaching, and environmental pollution.

The integration of microalgae into agricultural systems establishes a strong synergy between soil health improvement and climate change mitigation. By enhancing soil organic carbon through biomass production and decomposition, microalgae directly contribute to carbon sequestration, reducing atmospheric CO₂ levels while simultaneously improving soil structure and fertility [176]. During their decomposition, these microorganisms release EPSs, which serve as an easily accessible carbon source for soil microbiota, thereby supporting microbial growth and activity [125]. Furthermore, microalgae stimulating beneficial microbial communities and promoting nutrient availability, making them a vital component of sustainable agricultural practices and climate-resilient ecosystems [177,178].

Their application as biofertilizers, biostimulants, and biochar not only promotes soil rejuvenation but also aids in addressing climate change by decreasing reliance on fossil fuel-based agrochemicals and enhancing soil carbon retention. Healthy soils, rich in organic matter, sequester atmospheric CO₂ through processes like photosynthesis and organic matter decomposition, thereby reducing GHG concentrations [179,180]. The synergies between soil improvement and climate change mitigation are centered on the ability of healthy soils to act as carbon sinks, enhance ecosystem resilience, and support sustainable land management.

Recent evidence demonstrates that microalgae and their associated groups could improve crop resilience when facing abiotic stresses. For instance, applying microalgal extracts to *Chenopodium quinoa* under salt stress led to a higher accumulation of proline (which acts as an osmoprotectant) and boosted the activities of antioxidant enzymes, resulting in enhanced tolerance to salt stress [181]. Similarly, the combined cultivation of microalgae with plant-growth-promoting bacteria in saline environments greatly reduced yield losses by means of mechanisms such as the production of phytohormones, siderophores, the formation of exopolysaccharides, and the modulation of reactive oxygen species [182]. Furthermore, algal biostimulants increase salt tolerance in common beans, demonstrating that extracts from microalgae such as *D. salina* and *C. vulgaris* enhance the plants' ability to withstand salinity by promoting osmotic adjustment, proline accumulation, and improved nutrient uptake [183]. The results offer specific illustrations of how metabolites derived from microalgae, interactions between microalgae and bacteria, and feedback mechanisms among soil microbes and plants can directly enhance resilience against drought, salinity, and extreme temperatures in farming systems.

As photosynthetic organisms, microalgae are highly efficient at capturing atmospheric CO₂. This process effectively removes CO₂ from the atmosphere or industrial flue gases and stores it in the form of algal biomass [184]. Additionally, microalgae possess specialized CO₂ concentrating mechanisms that enhance carbon fixation efficiency, making them a crucial component of sustainable carbon capture solutions [25]. However, microalgae species vary in their tolerance to CO₂, which is a key factor in determining their suitability for biomass production. Species with higher CO₂ tolerance can efficiently utilize elevated CO₂ concentrations, leading to increased growth and carbon fixation. In contrast, species with low CO₂ tolerance may experience growth inhibition due to acidification of the

culture medium. For instance, *Scenedesmus* sp. can tolerate 10–20% CO₂ despite an optimal concentration of 2% [185].

Microalgae biochar has the potential to fulfill several complementary roles, including soil amendments, enhancing soil carbon stability, reducing GHG emissions, and minimizing dependence on energy-intensive agricultural inputs [6,186]. Its nutrient-rich composition and ion-exchange properties help maintain soil fertility, combat desertification, and reduce GHG emissions, promoting soil health and sustainable agriculture [187,188]. One of the valuable uses of biochar is as an alternative to activated carbon for remediating contaminated soils [189]. Incorporating carbon-rich biochar into soil enhances its nutritional and biological properties, boosts contamination resistance, and helps reduce GHG emissions, such as CO₂, CH₄, and N₂O, contributing to climate change mitigation [190,191]. The biological sequestration of CO₂ by microalgae helps mitigate GHG emissions while simultaneously restoring carbon-rich soils, addressing the interconnected challenges of soil degradation and climate change [192,193]. Biochar accomplishes these objectives by altering soil microbial activity, enhancing its physicochemical properties, and providing a medium for the adsorption of GHG [194]. According to [16], microalgae biomass (e.g., *C. vulgaris*) was cultivated and converted into biochar via slow pyrolysis at temperatures 500 °C. The resulting biochar exhibited a high carbon content (up to 60%) and stable aromatic structures, making it an effective long-term carbon sink. Hence, the application of biochar to soil not only sequesters carbon but also enhances soil fertility by improving nutrient retention and stimulating microbial activity.

6. Limitations to Exogenous Microalgae Efficacy in Agricultural Soils

The effectiveness of exogenous microalgae products in agricultural soils is far from uniform, as their interactions with native soil microbial communities are highly complex and context dependent. These outcomes are affected by a dynamic interplay of factors, including the identity, diversity, and abundance of resident microbes, as well as their ecological traits and functional roles within the soil ecosystem. Beyond microbial interactions, numerous environmental and biological variables, such as soil physicochemical properties, the applied microalgal species, inoculum density, and prevailing climatic conditions, strongly influence efficacy [18,195]. This variability makes it difficult to predict consistent benefits across different soils and cropping systems, underscoring the need for a deeper understanding of the mechanisms driving microalgae–soil–microbiome interactions.

Soil characteristics like pH, texture, organic matter content, moisture, and salinity can significantly affect microalgae colonization, persistence, and functional contributions [19,195,196]. Acidic or alkaline conditions can affect microalgal metabolism, cell membrane stability, and bioactive compound release [195]. Determining the optimal soil pH is vital when selecting species to maximize their functional potential. For instance, the acidophilic microalgae *Euglena mutabilis* and *Chlorella protothecoides* var. *acidicola* grew best at pH 2.5, generating monosaccharides and glycolic acid that aided heterotrophic bacterial activity [197]. This underscores their ecological role in promoting microbial interactions and bioremediation processes in acidic, metal-contaminated environments. In contrast, *Spirulina* sp. and *Microcoleus* sp. thrive under alkaline conditions, whereas many eukaryotic microalgae exhibit better growth and activity in neutral soils [198,199]. As a result, strains that perform well under controlled laboratory and greenhouse settings often fail to deliver consistent benefits under field conditions, where environmental fluctuations, microbial competition, and complex soil properties strongly influence outcomes. Under field conditions, the inherent complexity and heterogeneity of soils further contribute to variable results, often leading to inconsistent outcomes and difficulties in evaluating the overall success of microalgae applications [200,201]. These insights suggest that soil variability

plays a decisive role in determining the success of microalgae applications, emphasizing the need for soil-specific strategies and adaptive management approaches (Figure 2).

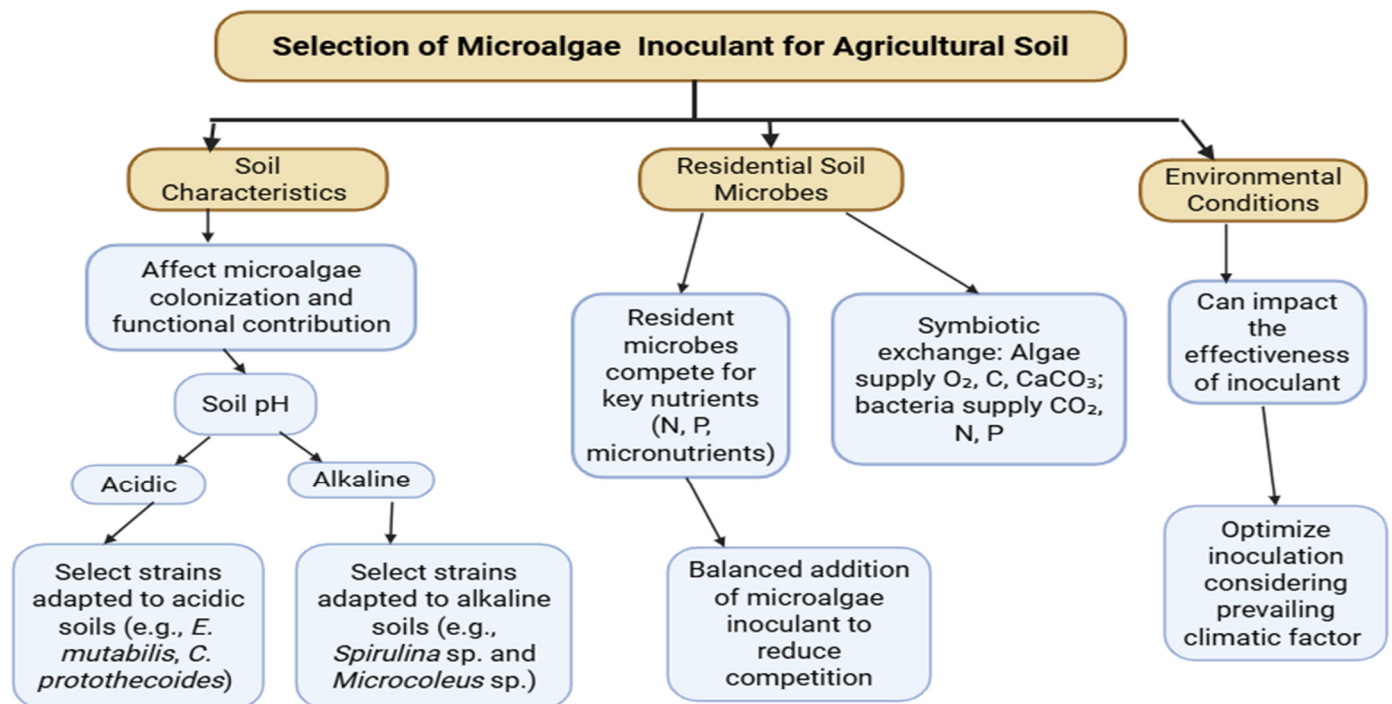


Figure 2. Flowchart for context-dependent selection of microalgae inoculants in agricultural soils.

Resident soil microbes, such as bacteria and fungi, often compete with introduced microalgae for key nutrients like phosphorus, nitrogen, and micronutrients. These interactions, ranging from symbiosis to competition or repulsion, can alter the soil micro-ecosystem's balance and affect vital biogeochemical processes [202,203]. Microalgal polysaccharides and phytohormones can provide carbon sources that stimulate microbial activity and enhance nutrient availability in the soil [176,204]. However, intensive additions of microalgal biomass may amplify competition for nutrients with resident soil microorganisms, potentially reducing the efficacy of the inoculum, particularly in nutrient-limited soils where microbial activity is constrained [205,206]. Overall, the limited understanding of how microalgae compete or cooperate with resident soil microbes remains a key barrier to predicting their consistent efficacy in agricultural soils.

Variations in environmental conditions can significantly impact the effectiveness of microbial inoculants, as these elements affect the survival and functionality of the introduced microbial strains as well as the indigenous microbial communities [207]. Microbial inoculants need to infiltrate, establish, multiply, and possibly disperse, and these processes collectively influence their effect on plant growth in conjunction with native soil microorganisms [208]. In light of this, it is suggested that integrating an ecological framework when assessing and utilizing microbial products may help forecast colonization success and consequently the positive results of inoculants.

According to [22], despite microalgae-based products' potential to enhance soil health, crop productivity, and reduce chemical inputs, their efficacy remains limited by a lack of ecological consideration during strain selection and development. This is largely due to selection based on laboratory traits rather than ecological compatibility, which limits their survival, activity, and appropriate persistence in diverse soil environments. They also point to the economic and logistical impracticality of designing and testing highly specific inoculants for every unique field condition, especially given the spatial heterogeneity of

soils. These challenges highlight the need for a more holistic, field-relevant approach to overcome soil and microbial constraints.

7. Challenges and Research Gap

Despite their significant potential, several challenges hinder the large-scale adoption of microalgae-based applications. A primary obstacle is the difficulty of achieving cost-effective biomass production at a commercial scale. Large scale production faces major challenges, such as high production costs, low biomass concentration, contamination risks, and energy intensive harvesting make it difficult to ensure a reliable and economical supply chain [23,209]. Energy-intensive cultivation, harvesting, and drying procedures, along with the requirement for nutrient supplementation and regulated growth conditions, are the main causes of the high cost of producing microalgae biomass. According to economic analyses, harvesting and dewatering alone can cost as much as 20–30% of the total cost of production, and drying or biomass processing can add 10–20% [210]. Other significant costs include nutrient inputs and mixing energy. Moreover, the relatively low biomass yield and high moisture content of microalgae increase the energy demand for drying and processing before biochar conversion, thereby reducing overall economic viability [211].

Microalgae cultivation is constrained by high energy and capital costs associated with artificial lighting, water demands, and energy-intensive downstream processing, which collectively reduce economic viability and sustainability for large-scale agricultural applications [7,24]. Studies on the production of microalgal biofuel, for instance, have shown that up to about 3000 L of water may be required per liter of product [212]. This suggests a significant water that might outweigh the advantages in semi-arid or drought-prone agricultural areas. These factors imply that utilizing microalgal biomass or products in regions with limited water supplies requires consideration of drought-tolerant strains, wastewater-based cultivation, water-recycling techniques, or low-water cultivation systems in order to reduce the consumptive water of algal biomass for soil amendment. According to Marra et al., [213], about 70% of the microalgae culture medium can be used again with *Pseudococcomyxa simplex* over three consecutive batch cultivations without affecting the specific growth rate or chlorophyll content. In contrast, under all tested conditions, they found that *Chlorella vulgaris* growth significantly decreased following the initial cultivation in the repurposed medium. Overall, water reuse offers a practical strategy to reduce both the water footprint and cultivation costs. However, the choice of microalgae species is crucial, though, as different strains exhibit varying capacities for growth and productivity maintenance in wastewater or repurposed media. Thus, in water-scarce areas, selecting species that can withstand medium recycling is crucial to obtaining consistent water-saving benefits.

Global climate change poses a number of stressors, including rising temperatures, changed rainfall patterns, changes in salinity, and pH, which have a substantial impact on microalgal growth, productivity, and ecological balance [214]. Particularly, in open-pond cultivation systems, excessive rainfall dilutes the growth medium and increases the risk of contamination [215], whereas drought conditions increase evaporation, concentrate salts, and impose osmotic stress, which restricts the growth of algae [216]. In order to maintain consistent biomass production under a variety of climatic conditions, it is crucial to choose species with a wide range of temperature tolerance as well as to optimize pond design.

As a more economical alternative, cultivating mixed algal cultures in nutrient-rich wastewater or agro-industrial effluents within open raceway systems is gaining attention to reduce costs [99,217,218]. For instance, wastewater media have reduced the cost of producing biomass from approximately 1.98 EUR/kg to 9.69 EUR/kg [219]. While using wastewater instead of synthetic media can significantly reduce on input use, the effects of

energy consumption on the environment are still problematic. However, in open raceway system, maintaining optimal cultivation conditions, such as stable CO₂ levels, pH, temperature, and light intensity, is also difficult, as fluctuations can affect growth rates and carbon fixation efficiency [220]. Closed photobioreactors offer controlled environments for monoalgal cultivation. Although their construction and operational costs are high, they can be 3–5 times less cost and energy-efficient than open systems, with harvesting and dewatering contributing 3–15% to total biomass production costs, substantially lower than the corresponding costs in open cultivation [221]. Integrating production with sustainable systems like wastewater treatment or biorefineries can boost scalability and cost-effectiveness [15].

Beyond cultivation challenges, processing methods also play a decisive role in determining the agricultural and environmental effectiveness of microalgae. For instance, dried microalgae treatments increase CO₂ respiration by 17% and microbial biomass carbon (MBC) by 38% compared to paste applications, highlighting the need to optimize processing techniques to reduce greenhouse gas emissions [72]. Furthermore, existing literature lacks detailed investigations into algal biochar preparation methods and their correlation with applications in soil improvement and carbon sequestration, highlighting the need for more focused and comprehensive research in this emerging field.

Although microalgae-based systems are effective for nutrient recovery and CO₂ sequestration, they can also produce nitrous oxide (N₂O), a potent greenhouse gas, through various biochemical pathways. This unintended N₂O emission may offset the environmental benefits of microalgae applications in wastewater treatment and reduce their overall greenhouse gas mitigation potential [222]. Moreover, algal residues with high nitrogen content can exacerbate microbial competition for inorganic carbon and promote gaseous losses, undermining the intended climate benefits [68]. Collectively, these studies highlight that while microalgal applications promise agronomic and environmental gains, they may paradoxically contribute to greenhouse gas emissions and nutrient inefficiencies if not carefully managed.

Therefore, several critical research gaps should be addressed to enable the widespread adoption of microalgae-based products for improving soil health and mitigating climate change. Unlike conventional chemical fertilizers, which frequently receive government support, biofertilizers made from microalgae are currently not supported by targeted subsidies or financial incentives for their production and commercialization [223]. The effectiveness of microalgae is influenced by factors such as soil type, cropping practices, and climate, which means that application protocols have yet to be standardized. Additionally, there is limited research on how different preparation methods impact soil carbon storage, nutrient cycling, and microbial activity, and the consequences of processing and formulation techniques, whether utilized as dried biomass, extracts, or biochar, are still not well understood. Moreover, the absence of clear regulations and quality certification standards, along with a lack of awareness among farmers and end users, poses challenges for market acceptance [37]. A thorough cost–benefit analysis of microalgae processing, from cultivation to market integration, is essential to identify economic bottlenecks and optimize resources. Addressing these challenges can enable microalgae to transform sustainable agriculture, carbon sequestration, and climate change mitigation.

8. Future Perspective

Future research on microalgae-based soil amendments should focus on overcoming the current technological, ecological, and economic limitations that hinder their large-scale adoption. One of the main priorities is still developing economical cultivation and processing systems. Integrating microalgae production with wastewater treatment or

biorefineries can increase economic viability while encouraging resource recycling and environmental sustainability.

Another key direction is the advancement of microalgal strains that are adapted to soil conditions. The majority of microalgae species thrive in aquatic environments and are not well-suited for terrestrial habitats. Consequently, the identification and cultivation of terrestrial or soil-dwelling species such as *Chlorococcum*, *Nostoc*, or *Scenedesmus* can improve their persistence and functionality in soil ecosystems. Applying adaptive laboratory evolution or genetic engineering could enhance tolerance to desiccation, salinity, and temperature fluctuations, traits vital for soil survival [224]. For example, research on *Scenedesmus* sp. IITRIND2 revealed that under elevated salinity, the microalga restricted ion channels, secreted EPS, and accumulated osmolytes such as proline and sugars, indicating coordinated metabolic adjustments that maintain cellular homeostasis and identify potential genetic engineering targets for enhancing salt tolerance [225]. Similarly, research by Schroda et al. [226] illustrated that the overexpression of the HSP70B gene in *Chlamydomonas reinhardtii* led to a substantial improvement in thermotolerance for the green alga by stabilizing photosystem II and safeguarding cellular proteins under elevated temperature conditions. The transgenic lines showed higher photosynthetic efficiency and growth rates compared to the wild type when subjected to heat stress, suggesting that strategically manipulating heat-shock proteins can improve resilience to temperature changes, a crucial attribute for soil endurance and applications geared toward climate resilience.

To strengthen field performance, co-inoculation strategies combining microalgae with plant growth-promoting rhizobacteria (PGPR) or mycorrhizal fungi can improve nutrient cycling, water retention, and microbial synergy [127,227–230]. Co-inoculation led to a reduction in acidity, enhancement of aggregate stability, an increase in soil nutrients, an improvement in the soil quality index, and superior plant growth compared to single inoculations. Moreover, advanced formulation techniques, such as encapsulation, biochar carriers, or hydrogel matrices, can safeguard microalgae from harsh soil conditions and prolong their active duration.

It is crucial to develop standardized application protocols that account for various soil types, climates, and cropping systems in order to assess and enhance the agronomic and environmental advantages of microalgal amendments. Long-term field trials should be prioritized to evaluate persistence, functional stability, and ecological impacts in real-world conditions. Future investigations should concentrate on assessing the ecological compatibility of microalgae through the examination of their interactions with indigenous soil microorganisms, plant roots, and environmental stresses. Understanding these interactions is crucial to ensure that microalgal applications enhance soil health without disrupting existing soil microbial communities or ecosystem balance.

Collectively, advancing microalgae-based applications requires multidisciplinary collaboration among researchers, industry, and policymakers to integrate biological innovation with practical field implementation. Addressing these research gaps will allow microalgae to play a transformative role in sustainable agriculture, soil fertility enhancement, and climate change mitigation.

9. Conclusions

Soil is the foundation of agriculture and climate resilience, and recent advancements in microalgae biotechnology offer new ways to restore and sustain this vital resource. These versatile microorganisms can significantly improve soil health, crop productivity, and environmental sustainability. Microalgae have potential to enhance soil health by promoting nitrogen fixation, P solubilization, nutrient cycling, enriching microbial communities, and producing bioactive compounds and EPSs that improve soil aggregation, soil structure,

water retention, and plant growth. With their high efficiency in CO₂ capture, biomass production, and carbon sequestration, microalgae present an effective tool for climate change mitigation. Further conversion of microalgae into biochar provides an eco-friendly approach to improving soil fertility, increasing carbon sequestration, and mitigating climate change by stabilizing organic carbon and supporting microbial activity. However, the efficacy of microalgae-based products is affected by a range of environmental and biological factors, such as soil physicochemical properties, microalgal species applied, inoculum density, and prevailing climatic conditions. Further, their commercial adoption is constrained by limited research and the high costs of production. Most studies focus on microalgae's potential at a laboratory scale, without addressing the practical challenges of integrating it into existing farming systems. To overcome these limitations, future efforts should focus on selecting field-adapted strains, employing mixed-strain inocula, conducting long-term field trials, optimizing formulation and delivery systems, and ensuring ecological compatibility with native soil environments. Further research is needed to develop precise application protocols, defining suitable methods, concentrations, and timings for different soils and crops, to enhance productivity, improve soil properties, and strengthen resilience to environmental stress. The next challenge lies in developing cost-effective cultivation systems, advancing biomass harvesting technologies, converting microalgal biomass into biochar, and optimizing metabolic pathways to enhance productivity and generate novel high-value compounds. Achieving these advances will harness the full potential of microalgae, driving soil health improvement, supporting a circular bioeconomy, and aiding climate change mitigation, ultimately fostering a more resilient and sustainable agricultural future.

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