

Review

# Harnessing Microalgae and Cyanobacteria for Sustainable Agriculture: Mechanistic Insights and Applications as Biostimulants, Biofertilizers and Biocontrol Agents

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## Abstract

The prolonged and intensive use of chemical inputs in agriculture, particularly synthetic fertilizers, has generated a variety of environmental and agronomic challenges. This has intensified the need for alternative, viable, and sustainable solutions. Plant-associated microbes have emerged as promising candidates in this regard. While research has largely focused on bacteria and fungi, comparatively less attention has been paid to other microbial groups such as microalgae and cyanobacteria. These photosynthetic microorganisms offer multiple agronomic benefits, including the ability to capture CO<sub>2</sub>, assimilate essential micro- and macrolelements, and synthesize a wide range of high-value metabolites. Their metabolic versatility enables the production of bioactive molecules with biostimulant and biocontrol properties, as well as biofertilizer potential through their intrinsic nutrient content. Additionally, several cyanobacterial species can fix atmospheric nitrogen, further enhancing their agricultural relevance. This review aims to summarize the potential of these microorganisms and their application in the agriculture sector, focusing primarily on their biofertilization, biostimulation, and biocontrol capabilities and presents a compilation of the products currently available on the market that are derived from these microorganisms. The present work also identifies the gaps in the use of these microorganisms and provides prospects for developing a suitable solution for today's agriculture.

**Keywords:** microalgae; cyanobacteria; biofertilizer; biostimulant; biocontrol agents; sustainable agriculture; circular bioeconomy; plant growth-promoting microorganisms



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## 1. Introduction

The rapid growth of the global population underscores an urgent need for sustainable solutions to ensure future food security, with FAO projections indicating that global food production must increase by 60% by 2050 [1]. Achieving this target requires the expansion of agriculture within a circular economy framework, where resource efficiency and environmental stewardship are prioritized [2]. However, the overexploitation of land, inefficient irrigation practices, and excessive use of chemical fertilizers and pesticides have degraded soil health, reduced biodiversity, and increased greenhouse gas emissions. Ultimately, these factors undermine the very crop productivity they were meant to support [3–5]. Soil health

(defined by its physical, chemical, and biological properties) is fundamental to sustainable agriculture. It supports plant growth, drives nutrient cycling, and strengthens resilience against pests, diseases, and climate change [6]. Traditional practices such as crop rotation, reduced tillage, organic fertilization, and cover cropping have long been used to maintain soil quality. However, these measures alone are not always sufficient. Innovative, nature-based microbial solutions are now emerging. These microorganisms can help restore soil structure, improve nutrient availability, and stimulate beneficial microbial activity, offering new tools for sustainable soil management. These approaches not only boost yields but also align with regenerative and low-impact farming methods essential for long-term food security and environmental sustainability [7,8]. Prioritizing soil health is essential for ensuring food security, conserving biodiversity, and promoting environmentally sustainable farming practices [6].

Plant and soil-associated microbial communities are fundamental to sustainable agriculture, as they support plant growth, drive nutrient cycling, and enhance resilience against pests, diseases, and climate change [9,10]. Although bacterial and fungal communities have been extensively studied over the past decades for these purposes, much less is known about other important microorganisms such as microalgae and cyanobacteria. These microscopic photosynthetic organisms inhabit soil, freshwater, and marine ecosystems and represent one of the most ancient and metabolically diverse groups of microorganisms on Earth. They possess an extraordinary capacity to convert carbon dioxide, sunlight, and inorganic nutrients into a wide array of valuable biomolecules, making them highly relevant candidates for agricultural innovation [11,12]. Thus, microalgae and cyanobacteria have been extensively studied for applications ranging from biofuels to pharmaceuticals [13–15]. Their high photosynthetic efficiency, fast growth rates, and ability to thrive in non-arable land and wastewater environments distinguish them from terrestrial crops and make them ideal candidates for circular bioeconomy models [16,17].

In recent years, microalgae and cyanobacteria have attracted growing interest also in the agricultural sector due to their multifunctional roles in enhancing plant productivity, improving soil health, and contributing to climate change mitigation through CO<sub>2</sub> sequestration [15,18]. Reflecting this potential, the global agricultural biologicals market is projected to reach \$14.6 billion by 2025, with algal and microbial biostimulants among the fastest-growing research areas [19]. In agriculture, a biostimulant is defined as a substance or microorganism that, when applied in small amounts, stimulates natural processes to enhance nutrient uptake efficiency, tolerance to abiotic stress, and/or crop quality, regardless of its nutrient content [20]. Biostimulants primarily act by improving plant physiological responses, enabling better growth and resilience under stress. The biochemical versatility of microalgae and cyanobacteria makes them particularly effective in this role [21] as they produce phytohormones, amino acids, polysaccharides, and antioxidants that boost photosynthetic performance, enhance antioxidant defenses, and promote the accumulation of osmoprotectants, especially under stress conditions such as drought and salinity [22]. Recent studies, including Brito-Lopez et al., 2025 [5] have confirmed their capacity to enhance plant growth and resilience across diverse environments, reinforcing their potential as climate-smart agricultural inputs. Compared to other commonly used biostimulants such as plant extracts, humic substances, or microbial inoculants based on bacteria and fungi, microalgae and cyanobacteria offer unique advantages. Their capacity to synthesize a wide range of bioactive metabolites, their high metabolic plasticity, and, in the case of some cyanobacteria, their ability to fix atmospheric nitrogen, enable them to function simultaneously as biofertilizers, biostimulants, and biocontrol agents [11].

The multifunctionality is particularly relevant given one of the central challenges in modern agriculture: the overreliance on synthetic nitrogen-based fertilizers and chemical

NPK inputs. While these compounds were key to the Green Revolution and have contributed significantly to global food security, their intensive and prolonged use has led to serious environmental and health consequences, including nitrate leaching, eutrophication of aquatic ecosystems, nitrous oxide emissions, and the decline of soil biodiversity [23]. These drawbacks highlight the urgent need for sustainable and environmentally compatible alternatives. Microalgae and cyanobacteria address this need by acting as biofertilizers that colonize the plant rhizosphere or tissues and enhance nutrient uptake [24–26]. Biofertilizers are natural preparations containing living microorganisms or other natural substances that, when applied to seeds, plant surfaces, or soil, promote plant growth by increasing the supply or availability of essential nutrients [27]. Their benefits include nutrient enrichment (e.g., nitrogen, phosphorus, potassium, and trace elements), production of plant growth-promoting substances (auxins, gibberellins, cytokinins), stimulation of beneficial soil microbial communities, and improved tolerance to both biotic and abiotic stresses [22]. Nitrogen-fixing cyanobacteria provide a compelling alternative to synthetic nitrogen fertilizers by mitigating the negative environmental impacts of conventional practices while maintaining or even enhancing soil fertility and crop productivity [28]. As the world faces the dual pressures of climate change and food security, harnessing the potential of microalgae and cyanobacteria represents a strategic pathway toward more sustainable and resilient food systems.

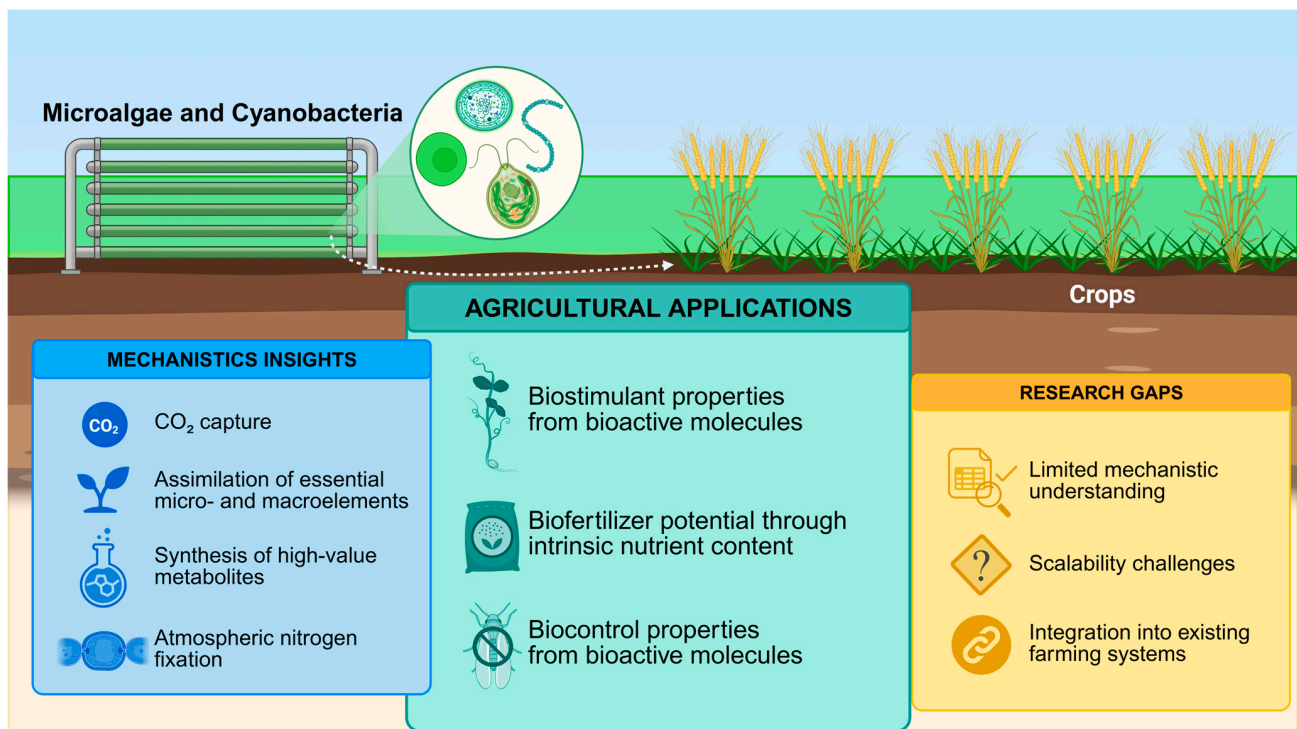
Building on this promise, microalgae and cyanobacteria offer specific practical solutions that further underscore their value in sustainable agriculture. Not only can they fix atmospheric carbon and accumulate nitrogen and phosphorus from various sources (including wastewater), but their application to soil can also release nutrients in bioavailable forms, reducing the risk of leaching and volatilization [29]. Furthermore, microalgal and cyanobacteria biomass can be integrated into regenerative agricultural systems, supporting nutrient recycling, organic matter enrichment, and improved soil structure [30–32]. Certain species such as *Chlorella sorokiniana*, *Scenedesmus obliquus*, and *Spirulina maxima* have already shown considerable promise as biofertilizers in field trials, with positive impacts on yield, root morphology, and chlorophyll content in a variety of crops including wheat, maize, tomatoes, and rice [5,26,30]. These benefits are further supported by recent findings showing significant reductions in synthetic fertilizer input without compromising crop yield [33].

Beyond their roles as biofertilizers and biostimulants, microalgae and cyanobacteria also exhibit significant potential as biopesticides. Many species produce a wide range of secondary metabolites (such as alkaloids, phenolics, peptides, and fatty acids) with antimicrobial, antifungal, and antiviral properties. These compounds can inhibit the germination of fungal spores, suppress the growth of phytopathogenic bacteria, and reduce the spread of viral diseases in crops [34]. Certain cyanobacteria additionally produce allelopathic compounds that interfere with pest development and reproduction, providing natural crop protection [35]. Overall, integrating microalgae- and cyanobacteria-based biopesticides into pest management programs offers a sustainable alternative for reducing chemical pesticide dependence and enhancing agroecosystem resilience.

Moreover, from a sustainability perspective, cultivating microalgae for agricultural applications supports circular economy and zero-waste approaches strategies [36]. Algal biomass can be produced using agricultural runoff, animal slurry, or even urban wastewater, thereby reducing waste streams and recovering nutrients that might otherwise cause pollution [31,32]. Additionally, in comparison to synthetic fertilizers, microalgal products can be produced with lower energy inputs and have significantly reduced carbon footprints when incorporated into biorefinery systems [37]. Despite these advantages, significant challenges remain for the large-scale implementation of microorganisms in agriculture, such

as economic feasibility, the scalability of production systems, and the need for standardized protocols and regulatory frameworks. However, ongoing advances in biotechnology, strain selection, photobioreactor design, and downstream processing are steadily improving the viability of microalgae-based agricultural products [38].

In summary, microalgae and cyanobacteria are emerging as powerful, nature-based solutions for advancing sustainable agriculture. These photosynthetic microorganisms possess the ability to produce a wide range of bioactive compounds that promote plant growth, enhance nutrient use efficiency, and contribute to soil health through nutrient cycling [15,18]. Their multifunctional roles as biofertilizers, biostimulants, and biocontrol agents make them attractive candidates for reducing dependency on synthetic agrochemicals, offering a path toward reduced environmental impact and improved agricultural resilience. Nevertheless, several challenges remain, particularly regarding cost-effective large-scale production and formulation. In this review, we address these gaps through a comprehensive and in-depth bibliographic search, synthesizing current scientific knowledge, compiling existing commercial products, and outlining future research priorities. By doing so, we provide a mechanistic and application-oriented framework intended to accelerate the integration of microalgae- and cyanobacteria-based solutions into sustainable agricultural practices. An overview of the present revision article is illustrated in Figure 1.



**Figure 1.** Overview of the present review. The figure illustrates the central agricultural applications of microalgae and cyanobacteria (as biofertilizers, biostimulants, and biocontrol agents), together with mechanistic insights (CO<sub>2</sub> capture, nutrient assimilation, metabolite synthesis, and nitrogen fixation) and the main research gaps (limited mechanistic understanding, scalability challenges, and integration into farming systems). Created in BioRender. Diaz Santos, E. (2025) <https://BioRender.com/3xt9h1a>, accessed on 19 March 2025.

## 2. The Use of Microalgae and Cyanobacteria as Biostimulants

Plant biostimulants are defined as substances or microorganisms that, when applied in small amounts, enhance plant nutrition processes, stress tolerance, growth, or quality, independently of direct nutrient supply [20]. Algae are recognized as some of the earliest plant growth promotion compounds used in agriculture, with historical records dating

back to the Roman era, where they were applied as manure to enrich soil fertility and promote plant growth, an application that has continued through the centuries. Thanks to their remarkable diversity and metabolic flexibility, microalgae and cyanobacteria serve as a rich source of high-value metabolites, including proteins, amino acids, enzymes, pigments, polyunsaturated fatty acids, polysaccharides, vitamins, antioxidants, and phytohormones [17,39]. This biochemical richness explains why these photosynthetic organisms are gaining increasing attention as sustainable inputs in agriculture as biostimulants [40]. Their demonstrated growth-promoting properties and environmentally friendly profile have contributed to their rising use particularly among growers seeking alternatives to synthetic agrochemicals. In the following section key factors in the development of microalgae- and cyanobacteria-based biostimulants products will be explored.

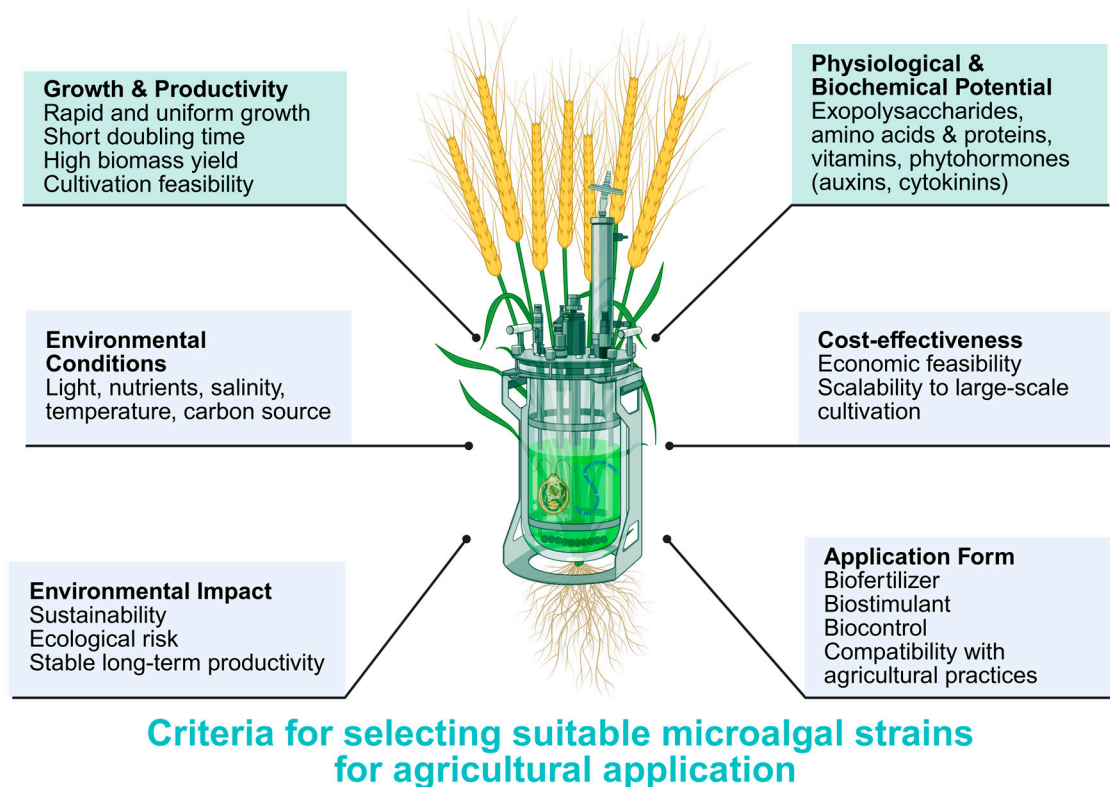
### 2.1. Cyanobacteria and Microalgae Strain Selection

Although microalgae and cyanobacteria hold great promise for agricultural applications, the selection of the most effective and context-appropriate strains remains a challenging task. This process requires access to well-characterized strains with a demonstrated high capacity for producing target bioactive compounds of agricultural relevance, while also being amenable to cost-effective, large-scale cultivation. Additionally, strains should exhibit adaptability to variable environmental conditions, stable productivity over time, and compatibility with existing agricultural practices to ensure practical implementation and long-term sustainability. Thus, among the key criteria for strain selection, two are particularly fundamental in determining whether a strain is viable for further development. The first is the strain's ability to grow rapidly and uniformly while maintaining high productivity (preferably in nutrient rich media or, in the best case, using waste-derived resources) to ensure the production of sufficient biomass. In this way, the strains must be easily cultivated to generate sufficient biomass [41,42]. Species such as *Chlorella vulgaris* and *Scenedesmus* spp. are well known for their fast growth rates and short doubling time [43]. The second essential criterion is the strain's physiological and biochemical potential, particularly its capacity to produce bioactive compounds such as exopolysaccharides, amino acids, proteins, vitamins, and phytohormone-like substances (e.g., auxins and cytokinins). In practice, an effective decision-making matrix for strain selection should integrate both production performance metrics (such as growth rate, biomass yield, and cultivation efficiency) and detailed biochemical profiles, including the concentration and diversity of target bioactive compounds. This integrated approach enables the systematic comparison of candidate strains, ensuring that the final selection balances productivity, functional quality, and suitability for large-scale, cost-effective biostimulant development (Figure 2). Based on these parameters, cyanobacteria and green algae currently represent the widely used groups in biostimulant applications and will be further discussed. In contrast, the application of diatoms in this context is still in its early stages of development.

### 2.2. Modes of Action and Mechanisms of Microalgae- and Cyanobacteria-Derived Biostimulants

Cyanobacterial and microalgal cellular extracts and hydrolysates are widely recognized as effective biostimulants capable of enhancing plant growth and increasing crop yields [44]. Their activity results from a combination of biochemical, physiological, and ecological mechanisms that collectively improve plant performance. Rather than acting through a single pathway, these microorganisms influence a network of processes that boost growth, optimize nutrient use efficiency, and strengthen resilience against environmental stresses. Application methods vary according to crop requirements and cultivation practices. Common approaches include incorporating live or dried biomass into soil, priming seeds with microalgal extracts, and applying root drenches. The choice of method is often

determined by whether the crop is directly sown or first cultivated in a nursery before transplantation to the field [45].



**Figure 2.** Selection criteria for the most suitable microalgal strain for agricultural application. The choice of an appropriate strain requires an integrated evaluation of multiple factors. Fundamental criteria include growth and productivity (growth rate, biomass yield, and cultivation feasibility) and physiological/biochemical potential (capacity to produce exopolysaccharides, amino acids, proteins, vitamins, and phytohormone-like substances). Additional factors such as adaptability to environmental conditions (light, nutrients, salinity, temperature), cost-effectiveness, application form (biofertilizer, biostimulant, biocontrol), and environmental impact (sustainability, ecological risks) further refine the decision-making process. Together, these criteria ensure the selection of strains that are not only productive and functionally relevant but also scalable, cost-effective, and sustainable for agricultural applications. Created in BioRender. Diaz Santos, E. (2025) <https://BioRender.com/kt10r85>, accessed on 19 March 2025.

The mechanisms (here defined as the specific biochemical, molecular, or physiological processes responsible for the observed effects) underlying the action of biostimulants in plants are still not fully elucidated. Their complexity makes them challenging to study, especially in the case of microalgae and cyanobacteria, whose extracts contain a wide variety of bioactive compounds. This diversity complicates the identification of the individual constituents responsible for specific effects. Nonetheless, recent advances in analytical and omics technologies, including next-generation sequencing (e.g., transcriptomics), deep phenotyping, and metabolomics, provide valuable insights into these intricate interactions [46].

The biostimulant effects of microalgae and cyanobacteria emerge from multi-layered interactions between their bioactive components and plant physiological and biochemical pathways. Thus, their modes of action (the overall functional outcomes through which these organisms exert their beneficial effects) are diverse, but can be broadly categorized as follows:

### (1) Enhancement of Nutrient Uptake and Assimilation

Although biostimulants are not primarily nutrient suppliers (a role fulfilled by biofertilizers, discussed in the next section), microalgae and cyanobacteria contain compounds that facilitate nutrient acquisition. Organic acids, chelating agents, and certain polysaccharides can mobilize micronutrients such as iron, zinc, and manganese in the rhizosphere [47]. Additionally, phytohormone-like substances (e.g., auxin- and cytokinin-like compounds) stimulate root architecture, increasing the absorptive surface area and indirectly improving nutrient capture.

### (2) Modulation of Plant Hormonal Balance

Bioactive molecules (including indole-3-acetic acid, gibberellin analogs, and brassinosteroid-like compounds) can modify the plant's endogenous hormone profile [48–50]. This modulation influences key developmental processes such as cell elongation, differentiation, and flowering, thereby improving plant vigor and productivity [51]. Certain hormones (particularly auxins, cytokinins, and ethylene) modulate root system architecture, increasing root surface area, branching, and exudation. These changes enhance the plant's capacity to explore the rhizosphere. In parallel, hormone-induced root exudates can stimulate beneficial soil microbiota, including nitrogen-fixing and phosphate-solubilizing microorganisms, creating a feedback loop that improves soil fertility. For instance, inoculation with *Calothrix elenkinii* stimulated the plant microbiome [52]. Additionally, phytohormones can upregulate the expression of nutrient transporter genes in roots, further facilitating the uptake of macro- and micronutrients [50]. Recent studies have shed light on brassinosteroid role in modulating agronomic traits that directly contribute to grain yield in rice (*Oryza sativa*) [53].

### (3) Activation of Stress-Response Pathways

Polysaccharides, proteins, and secondary metabolites in microalgal and cyanobacterial extracts can activate systemic tolerance mechanisms [5,54]. These include the upregulation of antioxidant enzymes (e.g., superoxide dismutase, catalase, and peroxidases) and the accumulation of osmoprotectants (e.g., proline, glycine betaine), which reduce oxidative damage and help maintain cellular homeostasis under drought, salinity, or extreme temperatures [54].

### (4) Improvement of Soil Microbial Communities

When applied to soil, whole biomass or extracts can serve as carbon and energy sources for beneficial microorganisms, fostering a more diverse and balanced microbiome for example, *Chlorella fusca* strawberry growth promotion correlates with changes in the plant microbiota, particularly the abundance of beneficial bacteria in the rhizosphere [55]. These bacteria can enhance nutrient cycling, particularly phosphate solubility, contributing to improved plant health, soil structure and stability.

## 2.3. Cyanobacteria and Microalgae as Biostimulants in Agriculture

Cyanobacteria are gaining attention in agriculture thanks to their ability to fix atmospheric nitrogen, solubilize phosphorus, and produce a wide variety of beneficial compounds (like phytohormones) that support plant health. Their unique physiological traits and metabolic flexibility have positioned them as promising biostimulants in crop production systems [56]. Certain genera, including *Anabaenopsis*, *Calothrix*, and *Anabaena*, have demonstrated the capacity to enhance seed germination and promote plant development through the synthesis of phytohormones like cytokinins, gibberellins, and auxins [57–59].

Beyond promoting plant growth, cyanobacteria also help plants cope with stress. For example, they produce extracellular polysaccharides, antioxidants, and signaling molecules

that help mitigate the damaging effects of salinity [25]. Under drought conditions, their benefits extend further: cyanobacteria can regulate ion export, modulate the surrounding microbial community, and even improve germination rates under limited water availability. These stress-alleviating traits have been documented across a wide range of crops, as reviewed by Sánchez-Quintero et al., 2023 [60]. Alongside their direct effects on plants, cyanobacteria also play a crucial role in soil health. In addition to acting as biofertilizers (enhancing nitrogen fixation and phosphorus availability, as discussed in the next section), they foster symbiotic relationships with other soil microorganisms, thereby reinforcing their value in sustainable and regenerative agriculture [2,61].

Moreover, unlike seaweed, which are typically collected from the wild, cyanobacteria can be cultivated in controlled environments like open ponds or photobioreactors. This allows for more consistent quality and optimized conditions for producing bioactive compounds [56]. Taken together, the contributions of cyanobacteria to sustainable agriculture are multifaceted. They enhance soil structure by secreting polysaccharides, improve fertility through nitrogen fixation, increasing porosity and water retention, and release growth-promoting substances. Moreover, they aid in reducing salinity, making phosphorus more bioavailable, and facilitating the recycling of agricultural residues. Whether applied as live cell suspensions or processed extracts, cyanobacteria consistently demonstrate significant potential to enhance plant vitality, productivity, and resilience.

Green microalgae have demonstrated a wide range of beneficial effects on crop growth and are increasingly recognized as promising inputs for sustainable agriculture. Microalgae-based products can enhance plant nutrition, improve overall crop performance, support key physiological processes, and increase tolerance to abiotic stresses such as drought and salinity [62].

Among the various genera studied, *Chlorella* stands out as the most used in agricultural applications [63,64]. Numerous trials using both fresh biomass and extracts from *Chlorella* strains have reported notable improvements in plant development and yield [65,66]. For instance, treatments with *Chlorella fusca* have been shown to enhance the growth of Chinese chives under field conditions [67]. In another example, soil-drenching with live *Chlorella* cells significantly increased biomass production in *Medicago truncatula* [66]. Complementary findings have been reported for other *Chlorella* species as well. *C. vulgaris* and *C. pyrenoidosa*, for example, have proven effective as biostimulants in salt-affected soils, supporting the growth of crops such as lettuce, rice, eggplant, and cucumber under saline stress [68]. Likewise, applications of *Spirulina platensis* have demonstrated growth-promoting effects on leafy vegetables like rocket, red bayam, and pak choi [69], further reinforcing the versatility of microalgae across diverse crop types. A key mechanism by which microalgae enhance plant performance is through the production and secretion of phytohormones, including auxins and cytokinins. In addition, they release exopolysaccharides that contribute to drought and salinity tolerance by improving soil water retention and nutrient availability. These compounds also supply organic carbon to beneficial soil microbes, fostering microbial activity and nutrient cycling. Expanding the range of beneficial species, inoculation with filamentous cyanobacteria such as *Calothrix elenkinii* has been found to stimulate both the phyllosphere and rhizosphere microbiomes, further supporting plant health and productivity [70]. While research continues to identify and characterize the most effective microalgae strains, current evidence clearly underscores the potential of green microalgae as valuable biostimulants. Their capacity to enhance plant growth, improve resilience to environmental stresses, and promote beneficial soil microbial communities makes them a sustainable and impactful tool for advancing modern agriculture.

#### 2.4. Diatoms as Biostimulants in Agriculture

Diatoms are an incredibly diverse group of microorganisms, with around 100,000 known species. They are easy and cost-effective to cultivate, which makes them an attractive source of bioactive compounds, many of which are already used in the pharmaceutical industry [71]. Although their application as biostimulants in agriculture is still limited, their unique structural and biochemical characteristics offer great potential. Studies have shown that diatoms, particularly *Navicula* species, can positively influence plant growth in species such as *Salix viminalis*, *Helianthus tuberosus*, and *Sida hermaphrodita* [72]. One of the most distinctive features of diatoms is their silica-based cell wall and the secretion of mucilage rich in sugars like mannose, fucose, and galactose. These properties can be utilized in the development of diatom-based fertilizers, which may enhance plant biomass and crop yields. Diatoms also possess phytoremediation abilities, as they can absorb heavy metals from the environment (including lead, zinc, nickel, cadmium, and titanium) [73]. As part of the next generation of sustainable fertilizers, diatoms could help improve plant growth and resilience, especially under stress conditions such as extreme climate events [72,74].

#### 2.5. Microalgae-Bacteria Consortia

Finally, the use of microalgae–microorganism consortia has emerged as a promising alternative to the traditional application of single microalgal or microbial strains for promoting plant growth. In such systems, microalgae supply oxygen and organic compounds that stimulate beneficial bacteria, while bacteria recycle nutrients that enhance algal growth [75]. These synergistic partnerships offer significant advantages by providing plants with a broader spectrum of essential nutrients and molecules (such as nitrogen, phosphorus, and potassium) through complementary metabolic interactions [75,76]. Thus, when microalgae are combined with nitrogen-fixing bacteria, the consortium can perform complex biological functions that individual strains cannot achieve alone [77]. For example, co-inoculation of *Anabaena cylindrica* with diazotrophic *Azospirillum* increased maize productivity [78]. This cooperative behavior not only enhances nutrient availability but also supports processes with valuable biotechnological applications [79]. Furthermore, the combined activity of microalgae and beneficial microbes can activate plant defense mechanisms, leading to the production of fungal enzymes and antibiotics that protect plants from pests and diseases [80]. Beyond agricultural benefits, microalgae–bacteria consortia, especially those involving nitrogen-fixing species, also hold great promise in the fields of biotechnology [79].

### 3. Biofertilizers

A biofertilizer is a substance containing specific microorganisms or other natural preparations that, when applied to seeds, plant surfaces, or soil, promote plant growth by increasing the supply or availability of essential nutrients [27]. These microorganisms or preparations improve plant growth by colonizing the rhizosphere or interior of plants. This process enhances the supply or availability of nutrients to the host plant. The product is administered to seeds, plants, or soil [11,81,82]. In addition, these eco-friendly approaches have been shown to improve crop productivity, nutrient profile, and plant tolerance to abiotic and biotic stress. The use of biofertilizers reduces the problems associated with chemical fertilizers and leads to more sustainable agriculture [27].

The utilization and marketing of biofertilizers commenced in the 18th century with the patenting of ‘Nitragin’, the first *Rhizobium* formulation, by Hiltner and Nobbe [83]. The classification of biofertilizers is based on their function and mechanism of action. The most widely employed biofertilizers comprise nitrogen-fixers (N-fixers), potassium solubilizers (K solubilizers), phosphorus solubilizers (P solubilizers), zinc solubilizers (Zn solubilizers), and iron solubilizers (Fe solubilizers) [84–86].

While traditionally most biofertilizers have been based on heterotrophic plant growth-promoting bacteria (PGPB), such as *Rhizobium* or *Azotobacter*, in recent years photosynthetic microorganisms (microalgae and cyanobacteria) have emerged as highly promising candidates for next-generation biofertilizers. These photosynthetic microorganisms are rapidly emerging as valuable alternatives or supplements to traditional biofertilizers, owing to their multiple functions, including the improvement of soil properties through biofilm formation and the enhancement of organic matter. Their multifunctional nature, combined with their ability to thrive in a wide range of environmental conditions, makes them a promising tool for promoting sustainable crop production [87]. Moreover, these biofertilizers can be categorized into two broad groups: (i) photosynthetic microorganism-based biofertilizers (microalgae and cyanobacteria), and (ii) non-photosynthetic microorganism-based biofertilizers (classical PGPR and fungi). In the following subsections, the discussion will focus on the roles of photosynthetic microorganism-based biofertilizers.

### 3.1. Cyanobacteria as Biofertilizers Beyond Nitrogen Fixation

Nitrogen deficiency is one of the most critical constraints to agricultural productivity worldwide, since nitrogen is an essential macronutrient for plant growth and development. To overcome this limitation, sustainable alternatives to synthetic fertilizers have been widely investigated. Among them, nitrogen-fixing biofertilizers have traditionally attracted major research interest in leguminous crops, where rhizobial inoculants establish highly efficient symbiotic associations within root nodules to convert atmospheric nitrogen ( $N_2$ ) into plant-available forms [79,82]. However, the use of rhizobia is restricted to legumes, limiting their applicability across broader agricultural systems. In addition, several free-living or associative diazotrophic bacteria (such as *Azospirillum*, *Azoarcus*, *Burkholderia*, *Gluconacetobacter diazotrophicus*, *Herbaspirillum*, *Azotobacter* and *Paenibacillus polymyxa*) have been demonstrated to fix nitrogen, and some have even been successfully formulated into commercial biofertilizers [27,83]. Yet, their nitrogen fixation efficiency is considerably lower compared to symbiotic microbes, and their performance is often inconsistent under field conditions due to competition with native soil microbiota, sensitivity to environmental stresses, and limited persistence in the rhizosphere [88].

By contrast, photosynthetic diazotrophic microorganisms such as cyanobacteria represent a highly promising and more versatile solution [89,90]. Members of the order *Nostocales* are photoautotrophic prokaryotes capable of fixing atmospheric nitrogen into ammonia ( $NH_3^+$ ), which can be directly assimilated by plants [91]. This process not only reduces dependence on chemical fertilizers but also contributes to soil fertility and ecological balance. Unlike rhizobia, cyanobacteria are not restricted to specific host plants, and unlike most free-living diazotrophs, they combine nitrogen fixation with photosynthesis, making them largely self-sufficient. Under nitrogen starvation conditions, *Nostoc* and related genera develop heterocysts—specialized thick-walled cells that create a microoxic environment enabling nitrogenase activity. These heterocysts are strategically distributed along the filamentous chains of vegetative cells, ensuring an efficient supply of fixed nitrogen to the colony and, ultimately, to the surrounding rhizosphere [92]. This dual capacity to fix nitrogen and support broader soil fertility highlights cyanobacteria as a powerful alternative for developing next generation biofertilizers.

The development of cyanobacteria-based biofertilizer (CBF) has been enabled by the potential characteristics of these prokaryotic photoautotrophic microbes [93,94]. It is worth noting that using cyanobacteria as biofertilizers is not a completely new concept in agriculture (Table 1). These organisms have already been studied extensively in various crop systems. For instance, notable advancements have been made in rice cultivation over the past few years, such as in Andalusian paddy fields [94]. Re-inoculation of cyanobacterial

isolates from this area as CBF has had a positive, significant effect on plant growth, with a significant increase in plant length of 127% recorded, as well as significant increases in grain weight and number per panicle. Similarly, a recent study investigated the potential of two cyanobacteria, *Anabaena vaginicola* ISB42 and *Nostoc spongiaeforme* var. *tenue* ISB65, as promising candidates for producing environmentally friendly biofertilizers for sustainable peppermint cultivation because they improve the quantity and quality of essential oils (EOs) by upregulating the key genes involved in the menthol biosynthetic pathway in *Mentha piperita* [95]. Furthermore, their potential as biofertilizers for cotton crops has recently been evaluated, demonstrating that reintegrating these beneficial species into agricultural ecosystems can enhance crop growth and maintain a balanced microbial environment [96]. Taken together, these results suggest that cyanobacterial biofertilizers could be a promising way to sustain rice production [94]. This contributes to the broader goal of achieving sustainable agriculture on a global scale [96].

Among eukaryotic microalgae, the use of *Chlorella vulgaris* and *Scenedesmus obliquus* suspensions, cultivated in maize drainage water, has been demonstrated to be a cost-effective, slow-release organic fertilizer on farmland, when applied to lettuce. The replacement of 50% of the nitrogen mineral fertilizer applied to lettuce by microalgae suspensions resulted in a significant increase in biomass production, reaching up to 2-fold. It has been demonstrated that this approach has the capacity to enhance lettuce fresh biomass and improve soil health [97]. Five species of algae were also evaluated in greenhouse conditions with pea plants (*Pisum sativum*) and in open field plots with spring wheat: the cyanobacterium *Arthrospira platensis* (*Spirulina*), the unicellular green microalga *Chlorella* sp., the red alga *Palmaria palmata*, and the brown algae *Laminaria digitata* and *Ascophyllum nodosum*. The results showed that *Chlorella* sp. and *Spirulina* increased total nitrogen and available phosphorus in the soil, with *Spirulina* also significantly enhancing nitrate levels. *Palmaria palmata* and *Laminaria digitata* significantly increased the concentrations of inorganic nitrogen compounds ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ). Moreover, *Chlorella* sp. was demonstrated to improve total phosphorus, nitrogen, and carbon contents in the soil, as well as available phosphorus, ammonium ( $\text{NH}_4^+$ ), nitrate ( $\text{NO}_3^-$ ), and pea crop yield [98].

Beyond nitrogen fixation, cyanobacteria provide additional plant growth-promoting benefits. They improve soil structure through biofilm formation [99]. In addition, they can increase soil porosity and decrease soil salinity [7]. *Nostoc* species possess the ability to produce phytohormones (auxins, cytochromes, gibberellins and ethylene), siderophores (iron binders) and mineral solubilizers (e.g., phosphorus, potassium and zinc) [100,101]. These symbiotic cyanobacteria have a wide diversity of associations with plants distributed throughout the plant kingdom such as spore-forming bryophytes, ferns, cycads or rice [102–104]. Special mention should be given to *Arthrospira platensis*, an edible cyanobacterium known worldwide for its high nutritional value, as well as for the interest in its biological activity and bioactive compounds [105]. Supplementing *Arthrospira platensis* by drenching the soil resulted in increased growth and productivity of chia plants cultivated under alkaline soil conditions, as well as increased antioxidant levels in the chia seeds. Following microalgae application, the oil content increased, as did the proportion of omega-3 [106]. More recently, according to [107], applying a biofertilizer containing *Spirulina maxima*, marine *Lactobacillus plantarum*, molasses, and industrial organic waste (IOW) at a concentration of 0.1% can enhance the growth, development, and nutrient uptake of rosemary plants by generating bioactive compounds, including vitamins, carbohydrates, and phytohormones (auxins, gibberellins, and cytokinins).

These findings highlight the potential of cyanobacterial biofertilizers as a multifunctional and sustainable tool for agriculture [94]. Their role extends far beyond nitrogen fixation, encompassing improvements in soil health, nutrient availability, plant physiology,

and crop productivity. Their application in staple crops such as rice suggests that cyanobacterial biofertilizers could become a cornerstone of sustainable food production in the years ahead.

### 3.2. Microalgae and Cyanobacteria as Biofertilizers: Nutrient Solubilization

Phosphorus (P) and potassium (K) are often limiting factors in agricultural soils, as both elements are commonly present in insoluble mineral complexes unavailable for plant uptake. This has led to growing interest in the development of phosphorus-solubilizing biofertilizers (PSB) [108]. Traditionally, various bacteria and fungi have been applied as PSB, including *Pseudomonas aeruginosa* in rice, *Pantoea agglomerans* in maize, *Pseudomonas* sp. in chili pepper, *Enterobacter* in soybeans, *Aspergillus niger* in beans, *Burkholderia cepacia* in peanuts, and *Azospirillum* in wheat [109–115]. However, beyond these classical microbial inoculants, photosynthetic microorganisms such as cyanobacteria and microalgae are increasingly recognized for their remarkable capacity to solubilize nutrients, representing a promising trend in sustainable agriculture. Species like *Nostoc* and *Anabaena* secrete organic acids and phosphatases that mobilize insoluble phosphates, while their extracellular polymeric substances (EPS) can chelate potassium and enhance its availability within soil aggregates. In addition, many microalgae not only solubilize P and K but also release bioactive metabolites and phytohormones, amplifying their plant growth-promoting effects [25,116]. This dual ability to improve nutrient bioavailability while simultaneously stimulating plant physiology gives cyanobacteria and microalgae a significant advantage over conventional PSB, positioning them as multifunctional biofertilizers with broad applications in sustainable agriculture.

Eukaryotic microalgae (*Chlorella*, *Scenedesmus*, *Chlamydomonas*) have also shown strong potential as P- and K-solubilizers. Although *Chlamydomonas* is not a strong nutrient-mobilizing species on its own, it can participate in associative biofertilization when co-applied with nutrient-solubilizing consortia; in such consortia, algal-derived metabolites support microbial activity that increases nitrogen and phosphorus availability to plants [75]. In addition, both microalgae can stimulate root growth through auxin-like activity while contributing to the mobilization or improved uptake of phosphorus and potassium, leading to better growth under nutrient-limited or stress environments [45,82].

### 3.3. Microalgae and Cyanobacteria as Biofertilizers: Siderophore-Mediated Growth Promotion

Micronutrient deficiencies, particularly zinc (Zn) and iron (Fe), severely limit crop productivity. In this context, Zinc-solubilizing biofertilizers have become increasingly important in the context of crop production. For instance, the process of zinc solubilization by certain bacterial species, including *Azospirillum*, *Azotobacter*, *Pseudomonas*, and *Rhizobium*, has been demonstrated to enhance zinc assimilation in wheat [117]. Furthermore, three selected different bacteria, *Acinetobacter calcoaceticus*, *Bacillus proteolyticus* and *Stenotrophomonas pavanii*, formulated in both free and encapsulated forms, showed improved plant growth parameters and enhanced zinc content in *Zea mays* and can be applied as biofertilizers to enhance soil fertility [118]. Zinc solubilization has also been observed in several *Chlorella* strains, where algal secretions mobilize insoluble Zn compounds, thereby enhancing plant Zn uptake [119–121]. The application of these algal inoculants could help address widespread micronutrient deficiencies in human diets by biofortifying staple crops such as rice and wheat.

Iron is involved in a variety of metabolic pathways within the cell, including photosynthesis, thus rendering it an essential element for plant life [122]. It is noteworthy, however, that siderophores represent a distinct group of low-molecular-weight compounds (less than 1.5 kDa) that exhibit a high affinity for Fe in environments with low Fe

concentrations [61]. The synthesis and secretion of these compounds by different microbial strains occurs under specific conditions, thereby increasing and regulating the bioavailability of Fe. Consequently, siderophore-producing bacteria have attracted considerable scientific interest because of their potential application as biofertilizers. These bacteria have been demonstrated to enhance soil fertility and increase plant biomass, a finding that is of significant relevance for the development of sustainable agricultural practices [123,124]. For instance, the promotional effect of the AS19 strain, a bacterium capable of producing high levels of siderophores and facilitating the absorption of Fe<sup>3+</sup> by seeds and plants, on the germination of pepper and maize seeds and the development of shoots and leaves of *Gynura divaricata* (Linn.) has been demonstrated [61]. In addition, a recent study has demonstrated the significant potential of Fe-solubilizing rhizobacteria (*Bacillus* spp.) isolated from the maize rhizosphere in calcareous soils as effective biofertilizers. These bacterial strains, namely *Bacillus pyramidoids*, *Bacillus firmicutes*, and *Bacillus cereus*, have the potential to mitigate Fe deficiency in crops, thereby promoting sustainable agriculture practices [125].

In addition to these examples, cyanobacteria such as *Synechococcus* and *Nostoc*, and microalgae like *Dunaliella* and *Chlorella*, can synthesize siderophores, which bind Fe<sup>3+</sup> and facilitate its uptake by plants. For example, *Synechococcus mundulus*-derived siderophores improved Fe bioavailability in maize, significantly enhancing chlorophyll content and photosynthetic efficiency [126]. Moreover, in relation to the *Cyanobacteria* spp., Brick et al., in 2025 [126] highlighted the significant potential of *Synechococcus mundulus*-derived siderophore in stimulating *Zea mays* physicochemical growth parameters and iron uptake. The results of this study indicate the capacity of cyanobacteria to synthesize siderophores as a sustainable substitute for synthetic iron chelators, and their role in the management of plant stress [126].

Notably, microalgae have been demonstrated to play a pivotal role in maintaining ion homeostasis. *Dunaliella*, a genus of algae, has demonstrated a remarkable capacity for adaptation to environments characterized by low iron levels. Several species of *Dunaliella*, namely *Dunaliella tertiolecta*, *Dunaliella salina* and *Dunaliella bardawil*, have been identified as originating from radically divergent environments. These species have been found to possess a unique family of siderophore-iron-uptake proteins [127]. Moreover, it has been demonstrated that *Dunaliella salina* extracts, particularly exopolysaccharides, have the capacity to promote the germination and growth of *Triticum aestivum* L. seedlings under conditions of salt stress, thus offering a potentially viable solution for enhancing the resilience of crops in salt-affected environments [128].

To conclude this section, Table 1 provides a summary of the main microalgae and cyanobacteria species with biofertilizer potential.

**Table 1.** Main microalgae and cyanobacteria species involved in biofertilization.

Species	Group	Biofertilization Mechanism	Plant/System	References
<i>Nostoc</i> sp.	Cyanobacteria	Nitrogen fixation, phytohormone production, solubilization of P/K/Zn	Wheat/In vitro Rize/Soil	[94,100]
<i>Anabaena vaginicola</i> ISB42	Cyanobacteria	Phytohormone-linked nutrient uptake, peppermint oil enhancement	Mentha/Greenhouse conditions	[95]
<i>Nostoc spongiaeforme</i> var. <i>tenue</i> ISB65	Cyanobacteria	Phytohormone-linked nutrient uptake, peppermint oil enhancement	Mentha/Greenhouse conditions	[95]
<i>Synechococcus mundulus</i>	Cyanobacteria	Siderophore production, enhanced Fe uptake in maize	Maize/In vitro	[126]
<i>Arthrospira platensis</i>	Cyanobacteria	Phytohormone production, improved nutrient acquisition in chia	Chia/Soil	[106]
<i>Spirulina maxima</i>	Cyanobacteria (marketed as microalgae)	Bioactive compounds enhancing growth and nutrient uptake in rosemary	Rosemary/Soil	[107]

Table 1. Cont.

Species	Group	Biofertilization Mechanism	Plant/System	References
<i>Chlorella vulgaris</i>	Microalgae	Nitrogen fixation Phosphorus and potassium solubilization, auxin-like activity	Lettuce/Soil	[45]
<i>Scenedesmus obliquus</i>	Microalgae	Nitrogen fixation P/K mobilization, root stimulation under stress	Lettuce/Soil	[45,129]
<i>Dunaliella salina</i>	Microalgae	Exopolysaccharides Siderophore-mediated Fe uptake under deficiency	Wheat/In vitro	[128]

## 4. Biocontrol Agents

Plants are constantly exposed to a wide range of biotic stressors, including fungi, bacteria, nematodes, insects, and viruses. In response, they have evolved complex and sophisticated defense mechanisms. The production of secondary metabolites plays a crucial role due to their effectiveness in pathogen and pest resistance [130]. Compounds such as saponin have been widely recognized for their antifungal activity and are considered key components of plant defense systems. These molecules can be harnessed to develop novel, eco-friendly strategies for disease control, reducing the environmental impact of chemical pesticides [131,132]. While many of these compounds are traditionally derived from plants, recent studies have identified the potential of microalgae and cyanobacteria as a promising alternative source of secondary metabolites, including alkaloids, flavonoids, terpenes, and essential oils [133,134]. Microalgae and cyanobacteria form beneficial associations with plants, which can enhance the production of secondary metabolites, especially under abiotic stress conditions. Among these metabolites, allelochemicals produced by these microorganisms have garnered particular interest due to their potential applications in sustainable crop protection and biocontrol strategies [134]. Microalgae and specially cyanobacteria, represent a prolific source of biologically active compounds involved in allelopathic interactions, many of which could be utilized for pest control and crop protection [96] (Table 2).

### 4.1. Phytopathogen Resistance

Allelochemicals from microalgae have demonstrated strong antimicrobial activity against a wide spectrum of phytopathogens. For instance, hapalindole T (an antibacterial alkaloid from *Fischerella* sp.), nostofungicin (a fungicidal lipopeptide from *Nostoc commune*), and eicosapentaenoic acid (antimicrobial fatty acid from *Phaeodactylum tricornutum*) are notable examples [135–138]. Moreover, cell extracts from *Chlorella vulgaris* and *Tetrademus obliquus* have been successfully applied to protect spinach crops against *Fusarium oxysporum* infections [139]. Gene editing in *Chlamydomonas reinhardtii* has also been used to enhance bacterial resistance in tobacco plants [140].

Several studies have evaluated the antifungal activity of microalgal extracts across diverse strains. *Anabaena* HSSASE11 and *Oscillatoria nigroviridis* HSSASE15 showed inhibitory effects against *Botryodiplodia theobromae* and *Pythium ultimum*, respectively, while *Dunaliella* HSSASE13 was effective against *Fusarium solani*. Similar antifungal results were reported for *Scenedesmus obliquus* extracts against *Sclerotium rolfsi* [141]. Interestingly, some microalgal extracts also show nematicidal activity. For example, *Scenedesmus obliquus*, *Chlorella vulgaris*, and *Anabaena oryzae* were able to inhibit the banana pathogen *Meloidogyne incognita* [142]. The antimicrobial activity of these extracts is largely attributed to phenolics, alkaloids, and peptides. However, in many cases, the specific active compounds have not been fully identified or characterized. While the mechanisms remain under investigation, the antifungal effects of phenolic compounds may involve interference with fungal cell wall biosynthesis [143].

#### 4.2. Microalgae and Cyanobacteria as Herbicides

The herbicidal potential of microalgae and cyanobacteria metabolites is an emerging field with encouraging preliminary findings. Several allelochemicals—mainly from cyanobacteria—have demonstrated phytotoxic activity. For instance, cyanobacterin, a phenolic compound produced by *Scytonema hofmanni*, inhibits photosynthetic electron transport. Similarly, nostocyclamide (a peptide from *Nostoc* sp.) and fischerellins (alkaloids from *Fischerella* sp.) interfere with photosystem II [144,145].

Other compounds like microcystins (peptides that inhibit protein phosphatases) and cryptophycins (polyketides that block microtubule polymerization) also show potential as herbicides [144,146]. Despite these findings, research on herbicidal compounds from eukaryotic microalgae remains limited, presenting an underexplored area with high potential for sustainable weed management.

**Table 2.** Main secondary metabolites from microalgae and cyanobacteria and their potential applications as biocontrol agents in agriculture.

Class of Compound	Characteristics	Microorganism	Underlying Mechanism of Biocontrol	Potential Target Pathogens/Pests	Potential Use in Agriculture	Experimental Evidence	References
Alkaloids	Nitrogen-containing heterocyclic compounds	<i>Fischerella</i> sp., <i>Calothrix</i> sp., <i>Desertifilum dzianense</i>	Interfere with DNA replication and protein synthesis in pathogens; disruption of cell walls.	Insects (neurotoxin), fungi ( <i>Agroathelia rolfsii</i> ), and broad microbial pathogens	Natural bioinsecticides or antimicrobial agents for biocontrol	in vitro bioassays	[147,148]
Polyketides	Structurally diverse metabolites derived from carboxylic acid precursors	<i>Gambierdiscus toxicus</i> , <i>Karenia brevis</i>	Inhibition of ion channels, disruption of cell signaling and membrane integrity	Plant-pathogenic fungi, bacteria; brevetoxins also toxic to invertebrates	Broad-spectrum fungicides or bactericides for crops	both in vivo (animal models) and in vitro; in vitro assays (channel agonist)	[149,150]
Fatty acids	Extracellular free fatty acids with allelopathic activity	<i>Chlorella vulgaris</i> , <i>Botryococcus braunii</i>	Membrane destabilization; inhibition of seed germination through allelopathy	Competing algae ( <i>Pseudokirchneriella subcapitata</i> ), weeds	Natural weed growth inhibitors (bioherbicides)	in vitro inhibition assays; in vitro allelopathic tests	[151,152]
Peptides	Non-ribosomal peptides biosynthesized by multifunctional enzyme complexes	<i>Anabaena</i> sp. PCC7120, <i>Microcystis</i> sp., <i>Planktothrix</i> sp., <i>Oscillatoria limosa</i> , <i>Synechococcus lividus</i>	Pore formation in membranes; inhibition of protein phosphatases; induction of oxidative stress in pathogens	Other cyanobacteria, aquatic weeds, possible cross-toxicity to pathogenic fungi/bacteria	Plant defense promoters or biostimulants	review (mostly in vitro); in vivo detection in hot springs; in vitro isolation/assays; in situ environmental surveys	[153–156]
Terpenoids	Organic compounds derived from C5 precursors with toxicity to invertebrates	<i>Nostoc commune</i> , <i>Calothrix</i> sp. PCC7507	Neurotoxic and deterrent effects on insects; oxidative stress induction	Bacteria ( <i>Bacillus cereus</i> , <i>S. epidermidis</i> , <i>E. coli</i> ), Insect pests (e.g., Lepidoptera larvae), nematodes; general herbivory deterrent	Natural insecticides or pest repellents	in vitro bioassays; review (includes in vitro and some in vivo reports)	[157,158]

#### 4.3. Microalgae and Cyanobacteria as Insecticides

Among all properties shown from microalgae and cyanobacteria extracts throughout this review, insecticide activity is another one proposed. There are several studies in which microalgae have demonstrated insecticide properties. In the case of diatoms or chlorophytes, the potential insecticide activity has been investigated. For example, the exploitation of *Chlamydomonas reinhardtii* extracts in the development of preparations combined with microparticles of zinc oxide was able to improve the larvicidal potential of *Tenebrio molitor* compared to zinc oxide alone treatment [159]. Another study has demonstrated that the extract from *Amphora coffeaeformis* and *Scenedesmus obliquus* presented larvicidal activity against *Culex pipiens* [160].

In another approach, biofilm-forming cyanobacteria were found to enhance plant defense mechanisms against insects. Some studies have demonstrated that biofilm from *Fischerella* ATCC 43239 increased the mortality of larvae from *Chirininus riparius*, demonstrating that the biofilm improves the production of allelochemicals with insecticide activity [161–164]. Moreover, biomass extracts from *Microcystis aeruginosa* 205 and *Anabaena circinalis* 86 showed high toxicity against larvae of *Aedes aegypti* [165]. Alternatively, some researchers have described that both unsaturated and saturated fatty acids are responsible for the insecticide activity of microalgae extracts against larvae from different species. Thus, the possible mechanism of larvicidal activity of fatty acids was investigated. The authors tested the inhibition properties of various fatty acids, demonstrating that linolenic and linoleic acids might have a dual mode of action against octopamine signaling pathways [166,167].

As a summary, Table 3 provides an overview of the main biocontrol-related agents identified with phytopathogenic resistance and herbicide and insecticide potential, together with their producing species, mechanisms of action, and target organisms.

**Table 3.** Overview of the main biocontrol-related agents identified with phytopathogenic resistance, herbicide and insecticide potential from microalgae and cyanobacteria. The table summarizes their mechanisms of action, producing species, and target pathogens or pests, highlighting their potential applications as natural alternatives to synthetic pesticides.

Biocontrol Mechanisms	Microalgae/Cyanobacteria	Produced Molecules	Mode of Action	Target Pathogens/Organisms	References
Phytopathogen resistance	<i>Fischerella</i> sp.	Hapalindole T (alkaloid)	Antibacterial activity	Phytopathogenic bacteria	[135–138]
	<i>Nostoc commune</i>	Nostofungicin (lipopeptide)	Fungicidal	Phytopathogenic fungi	[135–138]
	<i>Phaeodactylum tricornerutum</i>	Eicosapentaenoic acid (EPA, fatty acid)	Antimicrobial	Various pathogens	[135–138]
	<i>Chlorella vulgaris</i> , <i>Tetradismus obliquus</i>	Cell extracts (phenolics, peptides, not fully identified)	Inhibition of fungal growth	<i>Fusarium oxysporum</i> (spinach)	[139]
	<i>Chlamydomonas reinhardtii</i>	Genetic modification	Enhanced bacterial resistance via gene editing	Tobacco plants	[140]
	<i>Anabaena</i> HSSASE11	Phenolic/peptide extracts	Antifungal	<i>Botryodiplodia theobromae</i>	[141]
	<i>Oscillatoria nigroviridis</i> HSSASE15	Phenolic/peptide extracts	Antifungal	<i>Pythium ultimum</i>	[141]
	<i>Dunaliella</i> HSSASE13	Phenolic/peptide extracts	Antifungal	<i>Fusarium solani</i>	[141]
	<i>Scenedesmus obliquus</i>	Phenolic extracts	Antifungal	<i>Sclerotium rolfsii</i>	[141]
	<i>Scenedesmus obliquus</i> , <i>Chlorella vulgaris</i> , <i>Anabaena oryzae</i>	Phenolics, alkaloids, peptides	Nematicidal; possible inhibition of fungal cell wall biosynthesis	<i>Meloidogyne incognita</i> (banana pathogen)	[142]
Herbicides	<i>Scytonema hofmanni</i>	Cyanobacterin (phenolic)	Inhibition of photosynthetic electron transport	Weeds (phytotoxic effect)	[144,145]
	<i>Nostoc</i> sp.	Nostocyclamide (peptide)	Inhibition of photosystem II	Weeds	[144,145]
	<i>Fischerella</i> sp.	Fischerellins (alkaloids)	Inhibition of photosystem II	Weeds	[144,145]
	<i>Microcystis</i> sp.	Microcystins (peptides)	Inhibition of protein phosphatases	Weeds	[144,146]
	Various cyanobacteria	Cryptophycins (polyketides)	Blockage of microtubule polymerization	Weeds	[144,146]

Table 3. Cont.

Biocontrol Mechanisms	Microalgae/Cyanobacteria	Produced Molecules	Mode of Action	Target Pathogens/Organisms	References
Insecticides	<i>Chlamydomonas reinhardtii</i> + ZnO	Cell extracts	Enhanced larvicidal effect when combined with ZnO	<i>Tenebrio molitor</i>	[159]
	<i>Amphora coffeaeformis</i> , <i>Scenedesmus obliquus</i>	Cell extracts (fatty acids)	Larvicidal activity	<i>Culex pipiens</i>	[160]
	<i>Fischerella</i> ATCC 43239 (biofilm)	Biofilm-induced allelochemicals	Increased larval mortality	<i>Chironomus riparius</i>	[161–164]
	<i>Microcystis aeruginosa</i> 205, <i>Anabaena circinalis</i> 86	Biomass extracts	Toxic	<i>Aedes aegypti</i>	[165]
	Various microalgae	Unsaturated fatty acids (linolenic, linoleic acids)	Disruption of octopamine signaling (dual mechanism)	Insect larvae (various species)	[166,167]

## 5. Commercialized Microalgae- and Cyanobacteria-Based Products

An increasing amount of scientific research demonstrating the effectiveness of microalgae in agriculture has driven the development of an emerging and fast-growing market for microalgae-derived bioproducts. Commercial formulations such as Algafert, PhycoTerra<sup>®</sup>, and Spiralgrow have already entered the global market, targeting both conventional and organic farming sectors (Table 4). These products are offered as liquid concentrates, dry powders, or granules, and are often marketed for their ability to improve root development, nutrient uptake, and crop resilience under stress. Start-ups and aggrotech companies are also investing in vertically integrated production systems that combine algae cultivation with carbon capture and waste valorization, aligning with global sustainability goals [60]. According to recent market projections, the global microalgae-based biofertilizer segment is expected to grow at a compound annual growth rate (CAGR) exceeding 8% over the next five years, driven by regulatory shifts toward low-input agriculture and increasing demand for eco-certified inputs. This momentum underscores the transition of microalgae from an experimental innovation to a commercially viable and scalable component of sustainable agriculture [45].

Table 4. Examples of some commercialized microalgae- and cyanobacteria-based products.

Product Name	Manufacturer	Microalgae Used	Formulation	Main Effects	URL or Reference
Algafert	Biorizon Biotech	<i>Spirulina</i> spp.	Dry powder	Provides macro and micronutrients, promotes chlorophyll synthesis.	<a href="https://www.biorizon.es/en/products/biostimulants-y-bioenhancers/algafert/">https://www.biorizon.es/en/products/biostimulants-y-bioenhancers/algafert/</a> (accessed on 11 August 2025)
AgriAlgae	AlgaEnergy	<i>Nannochloropsis</i> spp.	Liquid biostimulant	Enhances photosynthesis, nutrient uptake, and crop vigor.	<a href="https://ag.algaenergy.com/es/product-category/agrialgae-premium/?lang=it">https://ag.algaenergy.com/es/product-category/agrialgae-premium/?lang=it</a> (accessed on 11 August 2025)
Allfertis	Allmicroalgae	<i>Chlorella</i> spp.	Powder	Promote resistance to biotic and abiotic agents; Increases the size and fruit weight.	<a href="https://www.allmicroalgae.com/en/agro/#Allfertis">https://www.allmicroalgae.com/en/agro/#Allfertis</a> (accessed on 11 August 2025)
Biofertilizer by MicroAlgaex	Microalgaex	Not specified—described as “microalgae formulations”	Liquid	Enhanced plant growth and yield, improved defense against abiotic stress, and increased nutrient absorption.	<a href="https://microalgaex.com/biofertilizer/">https://microalgaex.com/biofertilizer/</a> (accessed on 11 August 2025)
Ecotop	Herogra	<i>Ascophyllum nodosum</i> and blend of other microalgae	Liquid biostimulant	Enhances plant vigor, growth, and resilience to abiotic/biotic stress.	<a href="https://herograespeciales.com/en/productos/bioestimulantes/ecotop/">https://herograespeciales.com/en/productos/bioestimulantes/ecotop/</a> (accessed on 11 August 2025)
Kelpak	Kelpak	<i>Ecklonia maxima</i> (macroalga, used in synergy with microalgae)	Liquid biostimulant	Promotes root and shoot development, stress tolerance.	<a href="https://www.kelpak.com/kelpakintro.html">https://www.kelpak.com/kelpakintro.html</a> (accessed on 11 August 2025)
AlgaGrow	Plagron	Proprietary blend including cyanobacteria	Liquid biostimulant	Increases nutrient uptake and crop yield.	<a href="https://plagron.com/en/hobby/products/alga-grow">https://plagron.com/en/hobby/products/alga-grow</a> (accessed on 11 August 2025)

Table 4. Cont.

Product Name	Manufacturer	Microalgae Used	Formulation	Main Effects	URL or Reference
Seasol	Seasol International (Australia)	Blend of seaweed and microalgae extracts	Liquid concentrate	Broad-spectrum plant tonic.	<a href="https://www.seasol.com.au/products/seasol/">https://www.seasol.com.au/products/seasol/</a> (accessed on 11 August 2025)
Weed-Max	Trade S.A.E. Company (Egypt)	Cyanobacteria extract in powder phase	Dry powder	Suppress soil-borne fungi and enhance the antagonistic abilities of other bioagents.	[168]
Oligo-X algal	Arabian Group for Agricultural Service	Blue-green algal extracts in liquid phase	Liquid concentrate	Suppress soil-borne fungi.	[168]

## 6. Research Bottlenecks and Future Perspectives

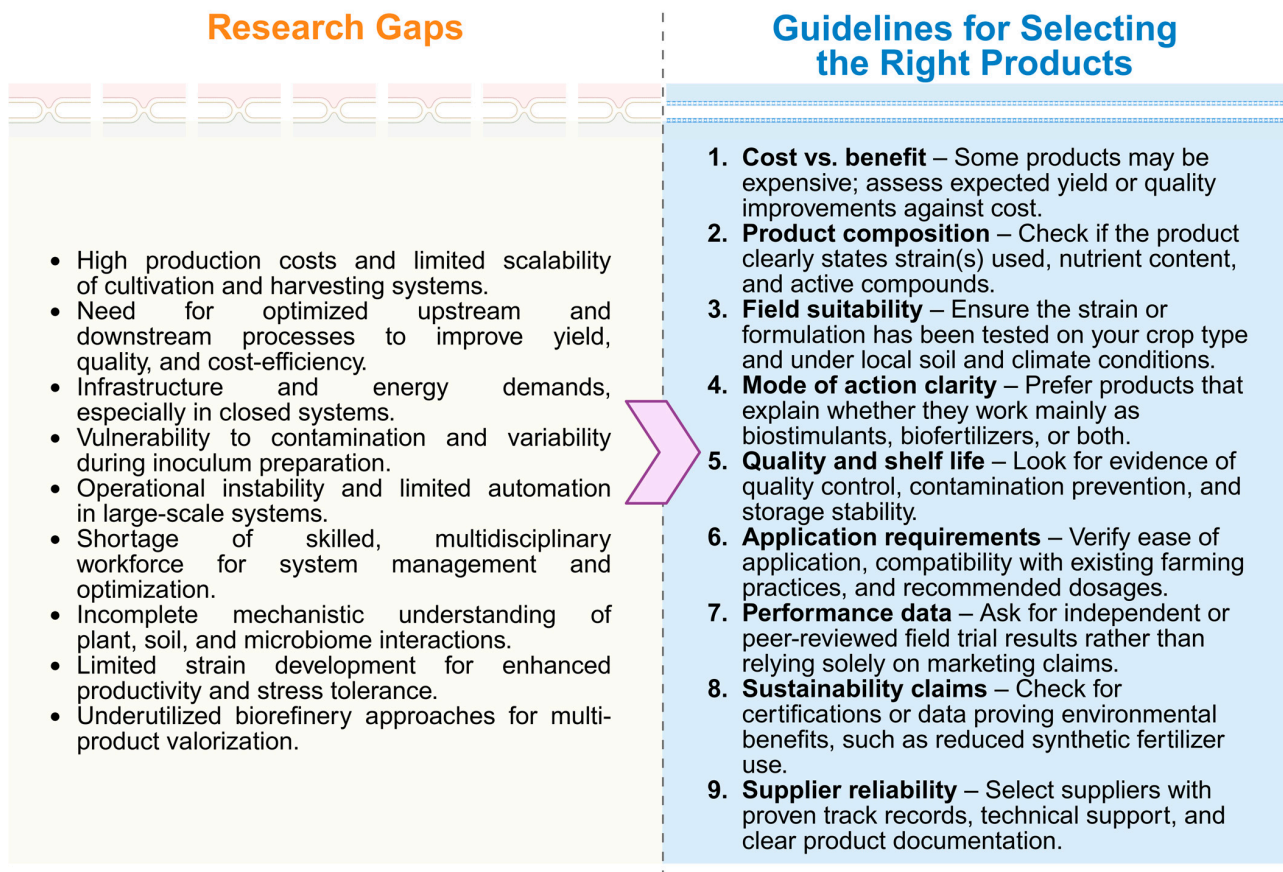
Microalgae and cyanobacteria have emerged as highly attractive candidates for sustainable agriculture and bio-based industries due to their distinctive biological and ecological traits. These photosynthetic microorganisms exhibit rapid and continuous growth, short generation times, and remarkable metabolic flexibility. Importantly, their cultivation does not compete with traditional agriculture for critical resources. They can be grown on non-arable land using saline water or even wastewater and rely primarily on sunlight as an energy source. These characteristics underscore their potential as complementary components to existing agri-food systems and as contributors to the circular bioeconomy, particularly in the production of food, feed, and high-value fertilizer products.

However, translating this potential into large-scale, economically viable operations presents significant challenges (Figure 3). Among the foremost constraints are the costs and efficiencies associated with cultivation, harvesting, and biomass processing. On the technical front, optimization of both upstream (e.g., growth conditions, nutrient supply, and biomass accumulation) and downstream (e.g., harvesting, extraction, and formulation) processes is essential to ensure yield consistency, biomass quality, and cost-effectiveness [38]. Infrastructure costs (especially for photobioreactors and open pond systems) are substantial, and operational expenditures such as lighting, temperature regulation, fluid circulation, cleaning, and biomass recovery remain high [169]. Closed systems, while offering advantages in terms of contamination control and process stability, are particularly cost intensive. Inoculum preparation constitutes another critical bottleneck; the reliability of large-scale operations depends on the production of high-quality starter cultures. Any microbial contamination or physiological variability during this stage can lead to serious disruptions, compromising the productivity of the entire system.

Operational stability is further challenged by routine maintenance, system downtime, and unexpected failures. Incorporating automation technologies offers a partial solution, reducing labor costs and human error while enabling real-time monitoring, improved safety, and enhanced process control. Nevertheless, successful deployment of these systems requires a multidisciplinary workforce with expertise in microbiology, bioprocess engineering, chemistry, and systems maintenance. Experienced personnel are indispensable for troubleshooting, process optimization, and quality control.

In parallel, a deeper mechanistic understanding of how microalgae and cyanobacteria interact with plant physiology and soil processes is critical to optimizing their use in agricultural contexts. Elucidating their modes of action (such as modulation of plant hormone levels, nutrient uptake, stress resilience, and microbiome interactions) is key to tailoring applications for specific crops, soil types, and climatic conditions. Such knowledge will improve consistency and efficacy under real-world field conditions. To overcome the current limitations, several strategies are under investigation. Continuous cultivation systems provide a stable operational platform and reduce the need for frequent re-inoculation. Increasing biomass density is another focus area, as it minimizes the volume that must be

handled during harvesting. Additionally, phycoprospecting efforts aim to identify naturally robust, high-performing strains, while genetic engineering approaches target enhanced productivity, stress resistance, and metabolite synthesis. Integrated biorefinery models are also gaining prominence, wherein multiple valuable compounds (such as proteins, pigments, fatty acids, and polysaccharides) are co-extracted from a single biomass stream, thereby increasing the overall economic viability of production systems.



**Figure 3.** Research gaps and practical guidelines for the selection of microalgae- and cyanobacteria-based products in agriculture. The (**left panel**) highlights current limitations in large-scale development, including high production costs, limited scalability, contamination risks, operational instability, and insufficient mechanistic understanding of plant–microbe interactions. The (**right panel**) provides guidelines for selecting appropriate products, emphasizing cost–benefit assessment, product composition, field suitability, mode of action clarity, quality and shelf life, application requirements, performance validation, sustainability claims, and supplier reliability. Together, these perspectives illustrate the challenges and practical considerations necessary for effective strain selection and product implementation. Created in BioRender. Diaz Santos, E. (2025) <https://BioRender.com/8wya7ti>, accessed on 19 March 2025.

In summary, while the upscaling of microalgae and cyanobacteria cultivation is constrained by technical and economic barriers, it also presents a promising frontier for sustainable agriculture and industrial biotechnology. With continued innovation in system design, strain selection, process automation, and bioproduct valorization, these microorganisms have the potential to become foundational components of resilient, resource-efficient, and climate-smart production systems.

## 7. Conclusions

The present review highlights the significant potential of microalgae and cyanobacteria as multifunctional biological resources in agriculture. Their diverse roles as biofertiliz-

ers, biostimulants, and biocontrol agents provide multiple agronomic benefits, including the improvement of nutrient availability, enhancement of plant growth and yield, and reinforcement of tolerance to biotic and abiotic stresses. At the same time, these microorganisms contribute to broader sustainability goals through nutrient recycling, carbon sequestration, and a measurable reduction in the dependence on synthetic fertilizers and pesticides. Their capacity to generate a wide variety of bioactive compounds, such as phytohormones, exopolysaccharides, and allelochemicals, underscores their versatility and makes them promising candidates for integration into environmentally friendly farming systems. Together, these findings confirm their relevance as key drivers in the transition toward sustainable and resilient agriculture.

Nevertheless, the translation of laboratory findings into large-scale applications remains limited. Several critical challenges must be addressed before their potential can be fully realized. Future research should prioritize:

1. Scalable cultivation systems—the development of cost-effective and energy-efficient production platforms, ideally integrating waste streams and renewable resources to minimize costs and environmental impact.
2. Formulation and delivery strategies—optimizing stable, field-ready formulations (e.g., encapsulation, consortia-based inoculants, or liquid suspensions) that ensure consistent performance under variable agronomic conditions.
3. Mechanistic understanding—advancing molecular and physiological studies to clarify the interactions between plants and microalgae/cyanobacteria, thereby identifying the key pathways responsible for plant growth promotion and stress alleviation.
4. Regulatory frameworks and standardization—establishing clear guidelines for safety, efficacy testing, and product approval to accelerate the transition from experimental studies to market-ready solutions.
5. Integration into circular economy models—exploring their role in waste valorization, nutrient recovery, and soil regeneration as part of holistic and climate-smart farming practices.

Overall, microalgae and cyanobacteria should not be regarded merely as alternative agricultural inputs but as integral components of next-generation, nature-based agricultural strategies. By coupling mechanistic research with technological innovation and policy development, their promise can be translated into scalable, commercially viable applications that contribute to global food security while reducing environmental impact.

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