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Algae As Bio-Fertilizer

Vaishnavi Joshi[1,*]

Abstract

Bio-fertilization represents a sustainable agricultural practice that leverages bio-fertilizers to enhance soil nutrient levels, thereby increasing agricultural productivity eco-friendly and feasible substitute for pollution-free agricultural applications, soil microflora has been used to increase biomass production and improve soil fertility. Numerous cyanobacteria, including species like Oscillatoria angustissima, Nostoc sp., and Anabaena sp., are known to be efficient nitrogen-fixing biofertilizers. Acuteodesmus dimorphus, Spirulina platensis, Chlorella vulgaris, Scenedesmus dimorphus, Anabaena azolla, and Nostoc sp. are other microalgae. Have been successfully employed to enhance crop growth, with Chlorella vulgaris being one of the most extensively studied species in bio-fertilizer research. Furthermore, the integration of seaweed species such as Sargassum sp. And Gracilaria verrucosa into soil has been shown to induce beneficial chemical changes, serving as indicators of soil fertility in clay and sandy soils. Seaweed conditioners enhance soil organic content, stabilize pH, and decrease the carbon-to-nitrogen (C/N) ratio, improving soil quality across various soil types. This review highlights the potential of environmentally friendly bio-based fertilizers, including microalgae and macroalgae, as effective strategies for enhancing soil fertility. These bio-fertilizers provide a sustainable alternative to inorganic and organic fertilizers, which are associated with negative environmental impacts, such as heavy metal accumulation and potential carcinogenic effects on human health.

Keywords: Bio fertilization, microalgae, macro algae, soil fertility, plant growth

INTRODUCTION

Agricultural success is heavily reliant on soil fertility, which serves as the cornerstone of organic farming systems. Fertile soil not only provides essential nutrients that plants require but also sustains a diverse and active biotic population, helping the soil resist environmental damage. However, heavy metals, naturally present in soil, have seen rising concentrations due to human activities such as mining, energy production, fuel manufacturing, electroplating, wastewater treatment, and agricultural practices. These pollutants are persistent in nature, meaning they cannot be broken down by microorganisms and thus remain in the environment indefinitely. Consequently, heavy metal levels often surpass safe limits in soil, water, and sediments. Metals like arsenic, mercury, chromium, nickel, lead, cadmium, zinc, and iron become toxic when present in excessive amounts (Pereira and Da Gama, 2008). Nitrogen deficiency is another issue that adversely affects plant growth, leading to stunted development, dwarf plants, leaf discoloration, and reduced yields. Recovery efficiency in many cropping systems is below 50%, with significant nitrogen losses occurring through volatilization, leaching, denitrification, and erosion (Chapman, 2013). Given these challenges, there is a growing global need for sustainable, eco-friendly bio-based fertilizers to enhance soil productivity and support pollution-free agricultural practices.

Biofertilization represents an environmentally sustainable approach, involving the use of biofertilizers to boost soil nutrient levels and improve productivity (Suleiman et al., 2020). Algae, which inhabit nearly all terrestrial environments, are

*Author for Correspondence
Vaishnavi Joshi
E-mail: joshivaishnavi118@gmail.com

[1]Scholar, Department of botany, School of Basic and applied Sciences, Shri Guru Ram Rai University, Patel Nagar, Dehradun, Uttarakhand, India

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among the most versatile organisms on Earth and offer immense potential for agricultural applications. They can act as biofertilizers and soil conditioners, enhancing soil fertility and plant productivity (Chapman, 2013; Duarte et al., 2018).

Soil algae, simple photosynthetic microorganisms found on or beneath the soil surface, thrive in the soil and contribute significantly to its health. They improve soil properties such as carbon content, aeration, texture, and nitrogen fixation. The interaction of algae with other organisms in diverse soil environments can serve as an indicator of a healthy soil ecosystem. Algae also help mitigate soil erosion by regulating water flow and play a vital role in soil restoration, fertility improvement, microbiological crust formation, pest control, and agricultural wastewater treatment (Abdel-Raouf et al., 2016). This review highlights the potential of environmentally friendly bio-based fertilizers derived from microalgae and macroalgae to enhance soil fertility, boost agricultural productivity, and remove heavy metal pollutants from the soil.

The rising global demand for food, driven by population growth and limited agricultural land due to urbanization and industrialization, has made food security a critical global challenge. Since the Green Revolution of the 1960s, intensive agricultural practices have relied heavily on high-yielding, disease-resistant crop varieties and the widespread use of chemical inputs such as fertilizers and pesticides. However, these chemical applications disrupt the natural balance of soil ecosystems and harm agro-biodiversity by eliminating beneficial soil organisms. Rice, a staple food for over half the global population, plays a central role in food security. According to the FAO's Rice Market Monitoring report, global rice production reached 741.3 million tons in 2014. Projections by Fageria indicate that by 2025, a 60% increase in rice production will be necessary to meet growing demand. To address this challenge, coordinated global efforts, including advancements in research and development, have been implemented to enhance rice production. These initiatives not only aim to meet food demand but also create job opportunities, increase farmers' income, and improve rice accessibility for underprivileged populations. Sustainable agricultural practices, such as the use of biofertilizers, have emerged as effective solutions for enhancing soil nutrient content, which in turn boosts productivity. Nitrogen deficiency significantly impacts rice production by stunting plant growth, causing dwarfism, yellowing leaves, and reducing yields. Current cropping systems demonstrate a nitrogen recovery efficiency of less than 50%, with substantial nitrogen losses attributed to volatilization, leaching, denitrification, and soil erosion. Algae, found in diverse terrestrial environments, hold significant potential in agriculture as biofertilizers, for soil improvement, wastewater treatment, and even as a source of biofuel. Cyanobacteria, particularly filamentous and heterocyst-forming strains, are integral to tropical rice field ecosystems. They serve as an efficient alternative to chemical fertilizers, contributing to nitrogen enrichment in rice fields with both economic and environmental advantages. These cyanobacteria can adapt to nitrogen-deficient conditions by forming heterocysts and utilizing photoautotrophy and diazotrophy, relying only on water, minerals, carbon dioxide, and sunlight for growth. In addition to blue-green algae (BGA), red and brown algae have also demonstrated their potential as effective biofertilizers, further underscoring the value of algae-based solutions in sustainable agriculture.

The Rise of Algae As Bio-fertilizers

Biofertilizers consist of living microorganisms that enhance the chemical and biological properties of soil, restore its fertility, and promote plant growth. Nitrogen is an essential nutrient for plants, and its deficiency can be addressed by applying adequate fertilizers. However, the excessive and prolonged use of synthetic or chemical fertilizers has caused significant contamination, ultimately disrupting the balance of ecosystems (Ritika and Utpal, 2014).

Historically, agricultural productivity has been limited by the availability of essential nutrients such as nitrogen and phosphorus. The development of the Haber-Bosch process in the 20th century marked a significant industrial advancement, enabling large-scale artificial nitrogen fixation. This process, which consumes approximately 1–2% of the global annual energy supply, is vital for producing nitrogen in a form that plants can readily utilize. Despite nitrogen's abundance in the atmosphere, its direct availability to crops remains limited because most plants lack the physiological mechanisms to assimilate atmospheric nitrogen. As a result, synthetic nitrogen fertilizers became essential. However, their production relies on finite, nonrenewable resources, incurs high costs, and is inaccessible for many resource-constrained farmers.

Synthetic fertilizers currently play a pivotal role in supporting the food demands of nearly one-third of the global population. However, their excessive use has led to adverse environmental impacts, including soil erosion, ecosystem degradation, increased vulnerability to pests and diseases, heightened water demand, and declining long-term soil productivity. Furthermore, their production contributes significantly to greenhouse gas emissions due to heavy reliance on fossil fuels. While synthetic fertilizers remain critical for meeting global food security needs, the shift toward organic and sustainable.

Agricultural practices highlights the need for environmentally friendly alternatives. Biofertilizers have emerged as a sustainable and effective alternative to chemical fertilizers. These formulations, comprising living microorganisms, enhance nutrient availability to plants by colonizing the rhizosphere, plant tissues, or soil. Biofertilizers include a wide range of organisms such as bacteria, fungi, cyanobacteria, and algae, as well as their metabolites, which collectively improve soil health, enhance crop growth, and increase yields.

Symbiotic nitrogen-fixing bacteria, such as Rhizobium spp., are commonly used with leguminous crops, while free-living nitrogen fixers like Azotobacter benefit crops like maize, wheat, cotton, and potatoes. Azospirillum species are particularly effective for crops like sorghum, millet, sugarcane, and wheat. Cyanobacteria, or blue-green algae (BGA), such as Nostoc sp., Anabaena sp., and Tolypothrix sp., are widely applied in rice paddies for their ability to fix atmospheric nitrogen. Additional biofertilizers include mycorrhizal fungi, organic fertilizers, and phosphate-solubilizing bacteria like Pantoea agglomerans and Pseudomonas putida, which release insoluble phosphates from organic and inorganic sources. The use of biofertilizers offers numerous benefits, including enhanced soil structure, increased water retention, reduced dependence on fossil fuel-derived inputs, and a boost in beneficial microbial populations. Cyanobacteria, in particular, play a critical role in improving soil fertility by increasing porosity, excreting plant growth-promoting substances such as auxins and gibberellins, and enhancing water retention through their gelatinous structures. They also contribute to the decomposition of organic matter, reduction of soil salinity, weed suppression, and phosphate mobilization.

Historically, the application of biofertilizers began with the introduction of Rhizobium-based "Nitragin" in 1895, followed by the discovery of other nitrogen-fixing organisms such as Azotobacter and BGA. Cyanobacteria, which date back over 3.5 billion years to the Precambrian era, have been extensively studied for their nitrogen-fixing capabilities, particularly in flooded rice ecosystems. Their application, known as "algalization," has demonstrated significant benefits for rice cultivation, including enhanced growth and yield while reducing reliance on synthetic inputs. In addition to their agricultural benefits, cyanobacteria have diverse applications, including biofuel production, environmental remediation, and pharmaceutical development. They represent a cost-effective and sustainable solution for nitrogen supplementation, improving soil fertility and crop productivity, and supporting an eco-friendly agricultural ecosystem. While research into the use of microalgae as biofertilizers is still evolving, initial findings suggest significant potential as a replacement for traditional chemical and organic fertilizers, paving the way for a sustainable agricultural future.

Algae Varieties for Enhancing Soil Fertility

Researchers investigated the effects of algae on plant growth, nutrient availability, and soil properties in greenhouse-grown garden peas and field plots of spring wheat. They utilized five distinct algae species with varying compositions. These included the cyanobacterium Arthrospira platensis (commonly known as Spirulina), the unicellular green algae Chlorella sp., the red seaweed Palmaria palmata, and two brown seaweeds, Laminaria digitata and Ascophyllum nodosum.

The findings revealed that Chlorella sp. and Spirulina Increased the soil's total nitrogen and available phosphorus, with Spirulina also raising nitrate levels. Palmaria palmata and Laminaria digitata significantly boosted inorganic nitrogen levels (NH_4^+ and NO_3^-) in the soil. Chlorella sp. Enhanced total nitrogen, phosphorus, carbon, available phosphorus, ammonium nitrogen, and boosted pea yields. However, algae additions had minimal influence on soil water-stable aggregates. In field experiments, Chlorella sp., Spirulina, P. palmata, and L. digitata all elevated soil inorganic nitrogen concentrations (Mahapatra et al., 2018).

Microalgae as Biofertilizers

Microalgae, which include eukaryotic green algae and prokaryotic blue-green algae (cyanobacteria), are photosynthetic microorganisms with vast potential in sectors such as medicine, healthcare, animal feed, and biofuel production. Their ability to enrich soil nutrients also makes them valuable for sustainable agriculture. These organisms can exist in unicellular, multicellular, filamentous, or mucilaginous forms and are among the world's most significant primary producers, with an estimated 200,000 species. The production of microalgae involves large-scale cultivation, biomass harvesting, and post-processing to deliver consistent yields for various applications, including food, chemicals, biofuels, and biofertilizers (Balasubramaniam et al., 2021). In agriculture, microalgae not only improve soil fertility and quality but also synthesize essential metabolites such as plant growth hormones, polysaccharides, and antibacterial compounds. Species like Spirulina sp., Chlorella sp., and cyanobacteria are particularly notable for their contributions to these processes (Ronga et al., 2019).

Cyanobacteria and green microalgae play a crucial role in agroecosystems by converting atmospheric carbon dioxide into organic biomass through photosynthesis, significantly increasing soil organic carbon content. They contribute to approximately half of global photosynthetic activity. Additionally, cyanobacteria's heterocyst cells fix atmospheric nitrogen, supplying essential nutrients to soil microorganisms, plants, and fauna. Research has shown that introducing cyanobacteria or consortia into crops enhances soil nitrogen levels and can reduce the need for chemical nitrogen fertilizers by 25–40%. Microalgae biomass contains bioactive compounds such as carbohydrates, lipids, proteins, and minerals, which can be extracted for various applications, including bioenergy and agriculture (Guo et al., 2020a; Tyoker Kukwa and Chetty, 2021). Extraction techniques depend on the desired final product and may include physical methods (e.g., bead milling, homogenization, microwave processing), chemical methods (e.g., solvents, acids, or alkalis), mechanical methods (e.g., ultrasonic or pulsed electric fields), and enzymatic treatments (Salinas-Salazar et al., 2019). These processes release valuable compounds from algal cells, enabling their use in multiple industrial and agricultural contexts.

Macroalgae as Biofertilizers

Macroalgae, commonly referred to as seaweeds, serve various purposes, including use as fertilizers, soil conditioners, animal feed, cosmetics, biofuels, integrated aquaculture components, and waste management tools (Khan et al., 2009). These marine plants are rich in bioactive compounds such as carotenoids, terpenoids, xanthophylls, chlorophylls, phycobilins, polysaccharides, vitamins, sterols, tocopherol, and phycocyanins, making them a valuable natural resource (Hashem et al., 2019). Despite their potential, seaweeds remain an underutilized resource globally (Osório et al., 2020). Sargassum, a rapidly growing brown macroalga, is notable for its antioxidant, carotenoid, and phenol content, including fucoxanthin, a compound with anticancer properties. This makes it a significant source of biologically and pharmaceutically important compounds (Silva et al., 2019). The genus Gracilaria is equally valuable, with over 300 identified species, 160 of which have been taxonomically classified. These algae are essential for industrial and biotechnological applications due to their capacity to produce large quantities of commercially viable biomass.

Sargassum is commonly found in temperate and tropical regions, inhabiting shallow waters and coral reefs, with some species free-floating. It is frequently washed ashore, where it is collected and used as fertilizer or a food source in certain regions. Seaweed fertilizers have been developed to enhance germination, improve root development, boost nutrient uptake, and increase crop yields. While seaweed has been used as a fertilizer since the 18th century, its application was initially confined to coastal areas. Coastal communities have long utilized drift seaweeds as soil conditioners (Nabti et al., 2016a). A study conducted In Central Java harvested Gracilaria verrucosa and Sargassum sp., rinsed the samples to remove soil contaminants, and sun-dried them to reduce moisture content. These dried seaweeds were further processed by soaking in fresh water to eliminate salinity and then ground into powder. The seaweed powder was mixed with sandy and clay soils in a 90:10 ratio for experimental treatments, while untreated soils served as controls. A randomized experimental design assessed soil fertility metrics such as organic content, pH, carbon-to-nitrogen ratio, water retention, and soil infiltration capacity (Khan et al., 2009; Chittora et al., 2020; Zou et al., 2021).

Impact of Macroalgae on Soil Organic Content

Soil organic content is a critical factor in determining fertility. Organic matter, defined by the FAO in 2017 as a complex mix of partially decomposed organic substances, supports ecosystems by buffering climate change effects, enhancing food production, and ensuring water availability. In experiments involving Sargassum sp. And Gracilaria verrucosa, soil conditioners derived from these seaweeds significantly increased organic content in both sandy and clay soils. However, clay soils naturally exhibited higher organic content due to their finer texture, which facilitates the breakdown of organic matter into smaller particles (Feller and Beare, 1997). The addition of Sargassum powder resulted in a greater increase in organic content compared to Gracilaria. This highlights the potential of seaweed-based soil conditioners to significantly enhance soil fertility, regardless of soil type. Such improvements in organic matter content directly contribute to better soil quality and productivity (Feller and Beare, 1997; Izzati, 2015) Figure 2.

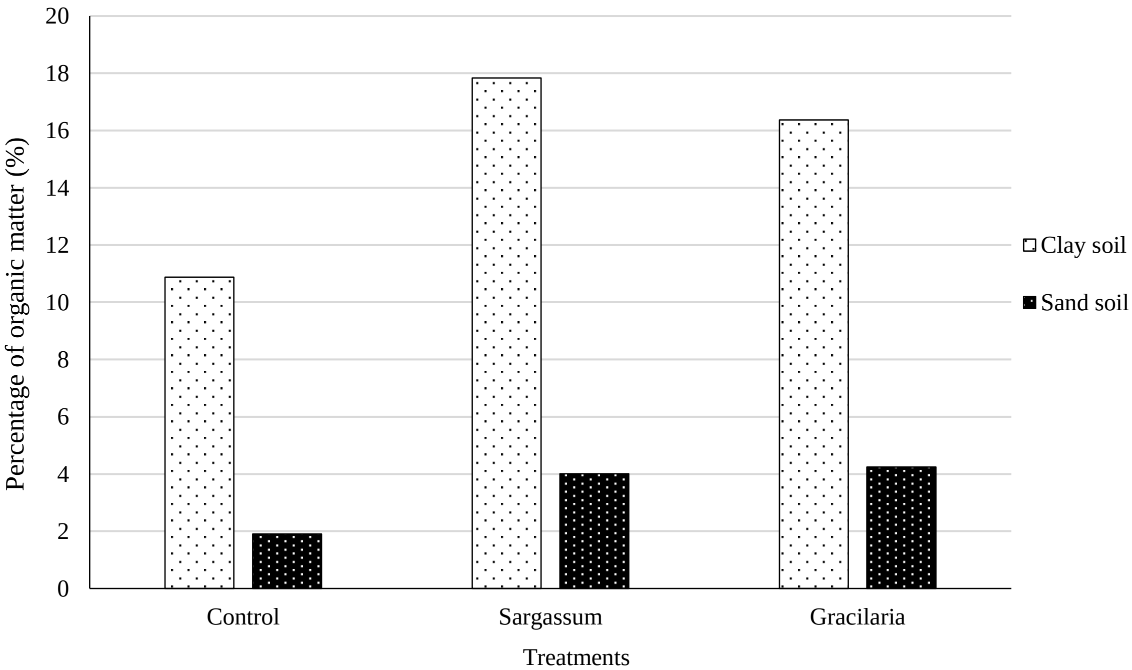

Figure 2. Effect of conditioners made from seaweed *sargassum* and *Gracillaria* on SC organic content.

Impact of Macroalgae as Biofertilizers on Soil pH

Soil pH, a key indicator of soil acidity or alkalinity, influences numerous chemical processes, including the chemical forms of nutrients that determine their availability to plants. Most plants thrive in soils with a pH range of 5.5 to 7.5. The application of seaweed-based soil conditioners has been shown to significantly alter soil pH. Initially, the soil in both tested media had a pH of approximately 8. After incorporating seaweed as a soil conditioner, the pH was notably reduced, approaching the neutral range around 7. Among the seaweed types tested, soil conditioners derived from Sargassum sp. had a more pronounced effect on lowering soil pH compared to those made from Gracilaria sp. (Izzati et al., 2019) Figure 3.

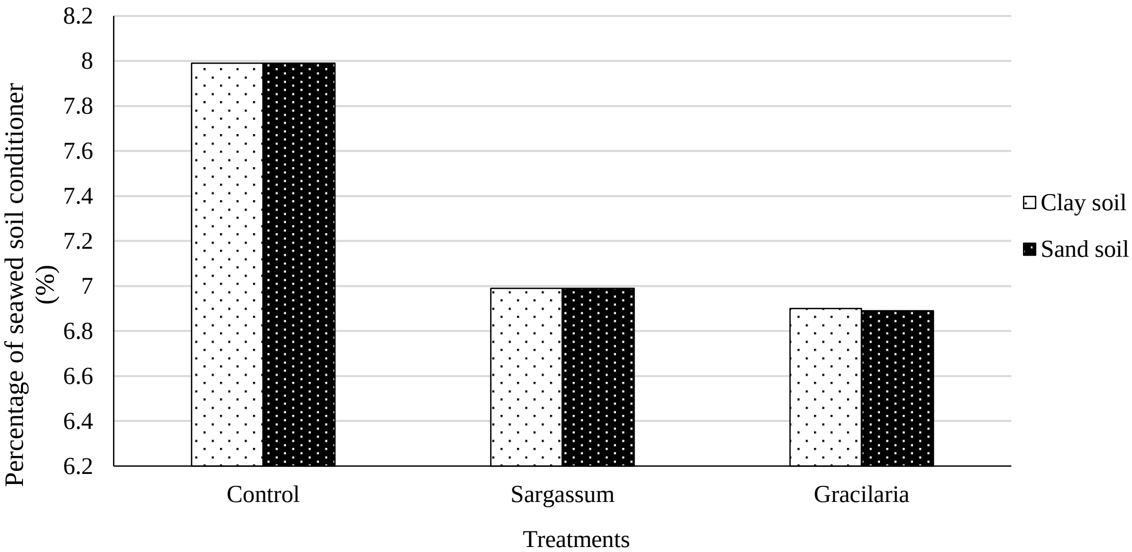

Figure 3. Effect of conditioners made from seaweed *Sargassum* and *Gracillaria* on soil pH.

Impact on Soil Physico-Chemical and Biochemical Properties

Various soil indicators are employed to evaluate the effects of fertilizers. Some focus on physical and chemical properties of the soil, while others emphasize biochemical characteristics that directly reflect the size and activity of soil microbial populations. This section explores the influence of algal biofertilizers on the physico-chemical and biochemical properties of soil, as well as their impact on native microbial communities.

Effect of Algae on Soil Aggregation and Porosity

Research by Rao and Burns [29] examined how the surface growth of inoculated blue-green algae (BGA) impacted subsurface properties in brown earth silt loam soils. Their study revealed a significant increase in soil polysaccharides and enzyme activities such as dehydrogenase, urease, and phosphatase. Additionally, they observed an improvement in soil aggregation, which is crucial for maintaining soil fertility. Burns and Davies [30] identified soil polysaccharides as key components responsible for soil stabilization. However, these benefits were primarily observed in the upper soil layer (0–0.7 cm depth). Similarly, Roychoudhary et al. [31] reported enhanced soil aggregation after incubation with BGA, leading to improved water retention. These findings have been corroborated by other researchers [32–34].

Algal proteoglycans, known for their adhesive qualities, enable cells to bind to solid surfaces, effectively aggregating soil particles [35]. The arrangement of these soil aggregates is vital as it directly influences soil temperature, aeration, and water infiltration, thereby enhancing the physical environment for crop growth [36].

In addition to soil aggregation, soil porosity can be improved by introducing Nostoc strains into clay soils, which mitigate the negative effects of water addition [36]. Cyanobacteria have also been shown to solubilize insoluble inorganic phosphate compounds, such as hydroxyapatite, tricalcium phosphate, and Mussorie rock phosphate [32, 37–40]. Studies by Bose et al. [38], Cameron and Julian [39], and Roychoudhary and Kaushik [40] confirm this phosphorus-solubilizing activity. Beyond phosphorus, multiple studies [41–43] have demonstrated increased nitrogen content and organic matter in soils treated with blue-green algae. These enhancements contribute to overall soil health and fertility.

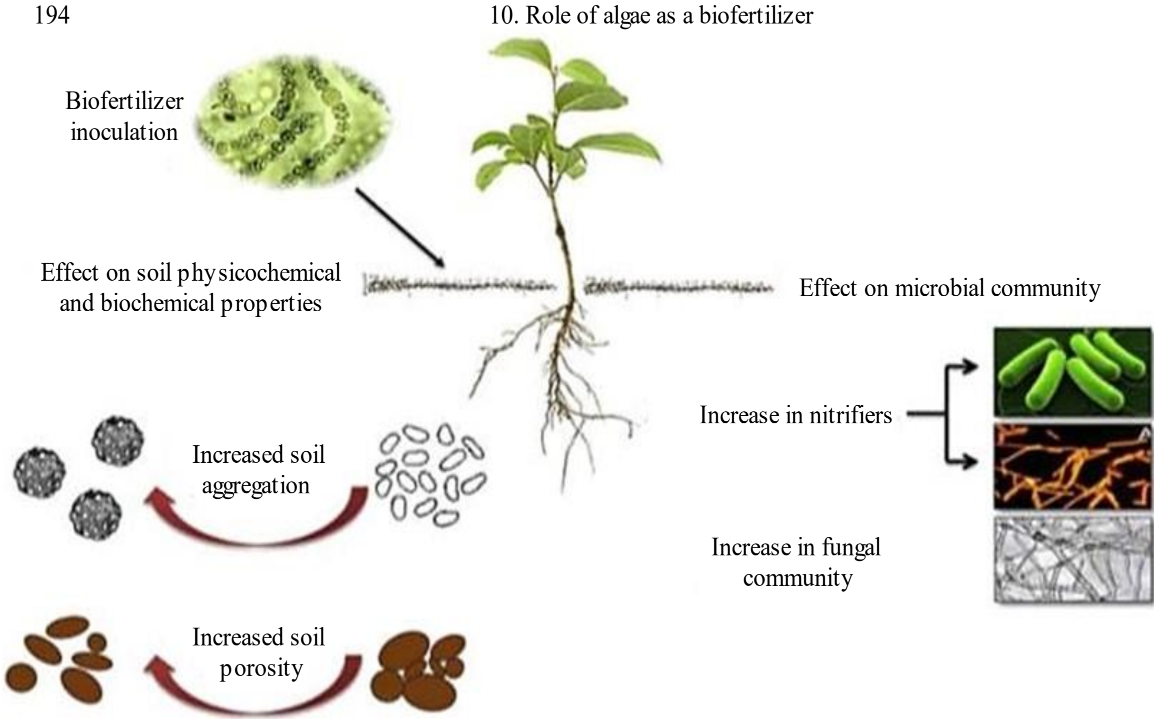

Figure 4. Effects of biofertilizers on physiological and biochemical properties of soil.

Effect on Soil Microbial Community

Although the impact of algal biofertilizers on soil microorganisms has been studied to some extent, the associated changes in microbial communities after introducing blue-green algae or other types of algae remain less understood. Rao and Burns [29] observed an eightfold rise in bacterial populations within soil columns treated with blue-green algae (BGA), though the fungal populations showed minimal changes. In a pot experiment, Ibrahim et al. [49] noted an increase in the overall microbial population, particularly nitrifying bacteria such as Azotobacter and Clostridium, following the application of Tolypothrix tenuis. Acea et al. [50] documented a significant rise in microbial groups, including heterotrophic bacteria, actinomycetes, algal cells, and fungal propagules, with over four logarithmic unit increases, while fungal mycelia increased by three logarithmic units when cyanobacteria were applied to burnt soils. Similarly, Rogers and Burns [51] reported a substantial shift in heterotrophic microbial populations upon inoculating soil with Nostoc muscorum.

These findings suggest that cyanobacterial polysaccharides, which provide additional carbon and energy sources, likely contribute to the observed growth in heterotrophic microbial populations. Moreover, the enhanced nitrogen content in treated soils supports the proliferation of native microorganisms. The soil's nutrient composition, particularly its nitrogen and phosphorus levels, plays a critical role in carbon mineralization, further influencing the structure and activity of the microbial community [52].

Advantages

Natural fertilizers can be used to create supplements that enhance soil's organic activity. The addition of tailored nutrients promotes plant health and supports growth. These nutrients nourish plants, encouraging the development of beneficial bacteria and soil organisms. Root growth is stimulated due to the improved soil structure. Organic matter content in the soil increases beyond normal levels. The growth of mycorrhizal associations is encouraged, which boosts phosphorus (P) availability in the soil. These fertilizers also help in preventing root diseases and provide a steady supply of essential micronutrients. They contribute to the stabilization of nitrogen (N) and phosphorus (P) in the soil, improving nutrient retention and exchange capacity (Carvajal-Muñoz and Carmona-Garcia 2012).

Genetically Modified Algae for Advancing Sustainable Agricultural Practices

Blue-green algae (BGA) are among the most resilient organisms, capable of surviving various abiotic stresses that limit crop productivity. Researchers have genetically modified algae from rice paddies to improve their nitrogen-fixing ability and stress tolerance, further supporting the goals of sustainable agriculture. Common herbicides like Machete and Basalin are used in paddy fields, and genes for herbicide resistance from an aerobic nitrogen-fixing Gloeocapsa strain have been successfully incorporated into the genome of Nostoc muscorum, providing it with herbicide tolerance. This advancement has significant potential for biofertilizer applications [69]. Additionally, Chaurasia et al. [70] reported that overexpressing the hetR gene, which controls heterocyst differentiation in Anabaena sp. Strain PCC7120, led to the formation of multiple heterocysts and increased nitrogenase activity, thereby improving nitrogen fixation.

CONCLUSION AND FUTURE PERSPECTIVES

The present chapter concludes that algal species have great potential in biofertilizer technology in terms of cost effectiveness, eco-friendly soil binders, amelioration of sodic soil, as Well as their natural occurrence in the paddy fields. Furthermore, the secretion of exopolysac-Charides and bioactive substances by algae and cyanobacteria has proven role in recovering Soil nutrients and mobilization of insoluble forms of inorganic phosphates. Development of Genetically modified stress-tolerant cyanobacteria has better prospect as biofertilizer and Transfer of stress coping genes into crop plants has a great future worth investing by the Researchers.

The soil must be sufficiently fertile to ensure high crop production, as plants rely on essential nutrients from fertile soil, which also supports a diverse and dynamic biological population that helps prevent environmental degradation. Biofertilization is a sustainable agricultural practice that involves using biofertilizers to increase soil nutrient levels and organic matter, leading to enhanced productivity. Both micro and macroalgae are environmentally friendly, bio-based fertilizers suitable for pollution-free agricultural applications. Microalgae tend to be more effective biofertilizers for soil than macroalgae, but macroalgae are more beneficial in large-scale aquatic environments. Additionally, microalgae can be rapidly reproduced in laboratory conditions, enabling bulk production. Microalgae show the highest levels of soil fertility in clay soil compared to sandy soil. Both types of algae can also be used for the removal of heavy metals.

Future Prospect, Undoubtedly, the use of bio-fertilizers represents the future of agriculture, with the potential to replace chemical fertilizers. Bio-fertilizers are safer for soil health and support biodegradation processes carried out by microorganisms, which ultimately enhances soil fertility in a natural, chemical-free way. There are also expectations to incorporate nanomaterials into bio-fertilizers, as nanotechnology could offer green and efficient solutions for managing plant diseases, improving plant resilience to environmental stress, boosting plant growth, increasing yield productivity, and enhancing both the quality and quantity of crops.

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