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ALGAE-BASED BIOFERTILIZERS: PRODUCTION, AGRICULTURAL APPLICATIONS AND SUSTAINABILITY

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ABSTRACT

Interest in algae-based biofertilizers has grown because they are rich in nutrients, promote plant growth and offer a more sustainable option than chemical fertilizers. Microalgae, macroalgae and cyanobacteria support crop productivity in three ways: they enrich the soil with nutrients, fix nitrogen and produce biologically active compounds. This review covers how these biofertilizers are made and formulated, from cultivation systems and biomass harvesting to the different product forms available. It also looks at their use in agriculture, mainly for better seed germination, root development, nutrient uptake, soil fertility and crop yield. The environmental benefits are highlighted as well, namely nutrient recovery from wastewater, use of carbon dioxide and a reduced need for chemical fertilizers. Yet some limitations persist. Production is expensive, formulations can be unstable, contamination is a risk and field performance is not consistent. Even so, algae-based biofertilizers are a promising route towards sustainable agriculture and better environmental management.

Keywords: Algae-based biofertilizers, Microalgae, Cyanobacteria, Agricultural sustainability, Soil fertility.

1 INTRODUCTION

Biofertilizers are biological preparations containing beneficial microorganisms or biological materials that increase the availability of nutrients, soil fertility and plant growth. They are important in promoting sustainable agriculture by reducing the dependence on synthetic fertilizers and promoting the natural recycling of nutrients [1]. However, excessive application of chemical fertilizers has led to a series of environmental problems, including eutrophication of aquatic ecosystems, nutrient imbalance, and soil degradation. These problems have generated increased interest in alternative nutrient management practices that are economically and environmentally sustainable [2], [3].

Potential alternatives have been developed based on algae-biofertilizers, due to their ability to supply vital nutrients and produce biologically active compounds that stimulate plant development. They are mainly sourced from microalgae, macroalgae (seaweeds) and cyanobacteria [4]. Microalgae such as Chlorella and Scenedesmus, and cyanobacteria such as Anabaena and Nostoc are of special interest because of their nutritional and plant growth promoting properties. Algal biomass is made up of nitrogen, phosphorus, potassium, amino acids, vitamins and essential micronutrients. Some algae also produce plant growth regulating substances like auxins, cytokinins and gibberellins which are important for seed germination, root development and crop growth [5], [6].

The application of algae-based biofertilizers can improve nutrient availability, support soil microbial activity and enhance crop productivity while reducing the environmental impacts associated with conventional fertilization [7], [8]. Their potential utilisation in wastewater treatment and nutrient recycling further supports sustainable agricultural practices. This review discusses the production and formulation of algae-based biofertilizers, their agricultural applications and mechanisms of action, and their environmental sustainability and major production challenges.

2 PRODUCTION AND FORMULATION OF ALGAE-BASED BIOFERTILIZERS

Algae based biofertilizers production requires selection of appropriate species of algae, cultivation of biomass, harvesting and formulation. Common organisms used include: micro-algae such as Chlorella and Scenedesmus; nitrogen fixing cyanobacteria such as Anabaena and Nostoc; and marine macroalgae or seaweeds. Their agricultural functions, growth characteristics, and nutrient composition are all subject to variation [9]. Microalgae are particularly important because of the nutrient-rich biomass that they produce, and cyanobacteria are particularly important for biological nitrogen fixation. Seaweeds are subjected to extensive processing to obtain extracts for agricultural use. These extracts are abundant in minerals and stimulate the growth of plants [10], [11].

Algal biomass is generally produced in open pond systems or closed photobioreactors. Open ponds are cheaper and better for large-scale production but photobioreactors allow better control of cultivation conditions, temperature, light exposure and contamination. The growth of biomass depends on factors like the intensity of light, temperature, pH and the availability of nutrients and supply of carbon dioxide. Nutrient sources such as wastewater and agricultural residues can lower production costs and enhance nutrient recovery [12]. After cultivation biomass is harvested by centrifugation, sedimentation or filtration and converted into granular formulations, liquid extracts or dried powders. The product should be processed, formulated and stored with care to preserve the quality, nutrient composition and biological efficacy of the product [13].

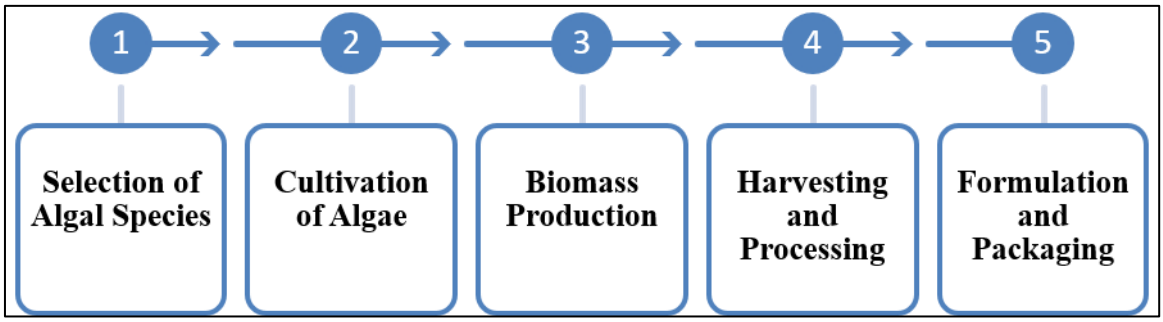

Figure 1: Steps of production of algae-based biofertilizers

Table 1. Major algal groups and production approaches used in algae-based biofertilizers

Algal group	Examples	Production approach	Agricultural significance
Microalgae	*Chlorella*, *Scenedesmus*	Open ponds and photobioreactors	Nutrient supply and plant growth promotion
Cyanobacteria	*Anabaena*, *Nostoc*	Controlled cultivation in nutrient media or suitable water systems	Biological nitrogen fixation and soil fertility improvement
Macroalgae (seaweeds)	*Sargassum*, *Ascophyllum*, *Ulva*	Seaweed collection or cultivation followed by extraction and processing	Mineral supply and plant growth stimulation

3 AGRICULTURAL APPLICATIONS AND MECHANISMS OF ALGAE-BASED BIOFERTILIZERS

Algae based biofertilizers are getting more and more explored to increase the growth and productivity of cereals, vegetables and horticultural crops. Depending on the algal species and crop requirements, they can be applied by different methods including seed treatment, soil incorporation, root application and foliar spraying [14]. There are a number of nutrient-related and biological mechanisms associated with their agricultural effectiveness. Cyanobacteria like Anabaena and Nostoc are nitrogen-fixing organisms that convert atmospheric nitrogen into a form that can be used

by plants. This decreases the need for nitrogen fertilizers. Certain microalgae also contribute to phosphorus solubilisation and improve the availability of essential nutrients [15].

Algal biomass contains phytohormones, amino acids, vitamins and other bioactive compounds which are stimulant for seed germination, root elongation, shoot elongation and overall development of plant. Also, algal biomass could be added to soil to increase organic matter, stimulate beneficial microbial activity, and enhance soil aggregation and water holding capacity [16]. These improvements contribute to better nutrient uptake and root development. Algae-based biofertilizers may also activate physiological and metabolic processes to improve plant resistance to environmental stresses, especially drought and salinity. Their application has therefore shown potential for improving crop growth, nutrient-use efficiency and agricultural productivity [17].

Table 2: Agricultural applications and mechanisms of algae-based biofertilizers

Application area	Major mechanism	Potential agricultural benefits
Nitrogen enrichment	Biological nitrogen fixation by cyanobacteria	Improved nitrogen availability and reduced synthetic fertilizer requirement
Phosphorus availability	Phosphorus solubilisation by certain algal microorganisms	Improved phosphorus uptake by plants
Plant growth promotion	Production of phytohormones, amino acids and vitamins	Enhanced seed germination, root development and shoot growth
Soil improvement	Addition of organic matter and stimulation of microbial activity	Improved soil structure, aggregation and water retention
Stress tolerance	Regulation of plant physiological and antioxidant responses	Improved tolerance to drought and salinity
Crop productivity	Improved nutrient uptake and plant development	Potential improvement in crop growth and yield

4 SUSTAINABILITY AND CHALLENGES

The use of algae-based biofertilizers represents a chance to decrease the environmental impact of conventional fertilization of agriculture. They can be produced and used to recycle nutrients, improve soil fertility and support more resource efficient agricultural systems. But there are several technical and economic limitations that need to be solved for their wider adoption.

4.1 Sustainability

The algae-based biofertilizers contribute toward environmental sustainability by reducing the dependence on synthetic fertilizers and by lowering the nutrient losses to the nearby water bodies. Cultivating them on wastewater and agricultural or industrial waste streams creates an opportunity to recover nutrients that would otherwise be wasted. Carbon dioxide is also used in algal cultivation for biomass production which contributes to recycling of resources and circular agriculture . Moreover, the use of algal biomass may improve soil organic matter, microbial activity and nutrient availability. Algae-based biofertilizers are promising components of sustainable crop production systems and integrated nutrient management due to these characteristics [18].

4.2 Challenges

They have a lot of potential, but there are several challenges to producing algae-based biofertilizers at large scale. Controlled photobioreactor systems can have considerable operational costs, especially for cultivation, harvesting, drying and processing. It is also difficult to maintain consistent biomass quality, product stability, and effective storage conditions. Furthermore, different algal species, environmental factors and soil properties may result in unstable agricultural performance. Contamination during cultivation, species-specific effectiveness and biosafety concerns associated with certain algal strains further require attention. Therefore, improvements in low-cost cultivation technologies, standardised formulations and field-level evaluation are necessary to support their wider agricultural application [19].

5 LITERATURE REVIEW

(Chojnacka et al., 2026) [20] Biofertilizers and biostimulants made from algae help crops grow better, use nutrients more efficiently and reduce harm to the environment. Seaweeds and microalgae carry useful compounds such as phytohormones, amino acids, osmoprotectants and polysaccharides, which encourage root growth and help plants cope with drought, salinity and heat. Cyanobacteria that fix nitrogen raise its availability and aid nutrient supply around the roots. Algal biomass can also be used for bioremediation, where it removes heavy metals, recovers phosphate and encourages the breakdown of pesticides. Field trials report higher crop yields, along with scope to cut chemical fertilizer use and nutrient losses. Still, biomass composition varies, shelf life is short, and working out the right application dose is hard. Controlled cultivation, careful strain selection and improved formulations like microencapsulation could make products more stable and effective. Integrated algal biorefineries further open routes toward sustainable production and circular farming systems.

(Kumaran et al., 2026) [21] The authors explored whether pairing biochar with algae-based biofertilizers can bring degraded soil back to health, mainly by improving fertility and fixing pH problems. Biochar neutralises acidic soils, and its porous structure helps nutrients stay in place. Algal biofertilizers do a different job: they fix nitrogen from the atmosphere and encourage plant growth. Together, the two make a durable solution to several farming problems. Biochar retains nutrients, steadies pH and gives beneficial bacteria a place to live, while algae make more nitrogen available, build soil aggregates and diversify the microbial community. Because this approach deals with soil degradation, carbon sequestration and nutrient shortage, it can lift crop yield and sustainability considerably. The results are promising, but some obstacles remain. Application rates need optimising, algae and biochar must be shown to work well together, and the method has to be adjusted for different soils and climates.

(Yadav S.G. Department, 2025) [22] This paper looks at what algae mean as biofertilizers biologically, environmentally and socially, and how they contribute to sustainable development. The group covers marine macroalgae (seaweeds), cyanobacteria (blue-green algae) and green microalgae, all of which fix nitrogen, photosynthesise efficiently and produce phytohormones. Because of this, they can restore soil health naturally, promote plant growth and make nutrients easier to access. The polysaccharides they secrete also improve soil structure and water retention, which is useful in dry or degraded land. On the economic side, algae cut input costs, and small-scale farming and processing units create jobs in rural areas. Bringing algal systems into wastewater treatment and bioenergy production supports circular bioeconomy principles as well. Still, few farmers know about these products, production is costly and regulation is inadequate, so wider uptake needs public education, supportive policy and technological innovation.

(Miranda et al., 2024) [23] Microalgae hold commercial promise across several industries. In modern agriculture they are especially useful, since besides supplying nutrients to soil they can produce plant growth hormones, polysaccharides, antibacterial compounds and other metabolites that raise farm output. Microalgae-based biofertilizers and biostimulants are therefore beneficial for farming and are promoted as an innovative, sustainable option. Yet bioformulated products break down quickly, so preparation is difficult and shelf life suffers. To give a thorough review of microalgae-derived biofertilizers and biostimulants, the authors ran a bibliometric analysis to spot trends through scientometric indicators, identified technological advances in formulation methods, and examined the global market for these bioproducts.

(Ma et al., 2024) [24] A hawthorn orchard served as the test site for a live microalgae-based biofertilizer, applied at three dosages and by two methods. The researchers recorded fruit output and quality, greenhouse gas emissions, and fractions of soil organic carbon and nitrogen. Medium doses applied at the roots clearly increased soil dissolved organic carbon, microbial biomass carbon, ammonium nitrogen and dissolved organic nitrogen, and soil organic carbon showed a rising trend too. The findings suggest that live microalgae, particularly at medium root doses, work as a green biofertilizer that raises fruit output while leaving GHG emission intensity and the total warming effect unchanged. The authors assume that if chemical fertiliser rates were lowered, nitrous oxide emissions could fall without hurting fruit quality or yield.

(Ghosh et al., 2022) [25] Using algae-based biofertilizers to manage food supply is one of the most environmentally friendly and sustainable innovative strategies. One of the most promising sources of potential biofertilizers is algae, which use large-scale biomass generation to biologically convert solar energy and different gases (including carbon dioxide and nitrogen) into high-value chemical compounds (like biofertilizers). Algal biofertilizers can therefore replace conventional chemical biofertilizers due to their omnipresence, accelerated metabolic flux, short generation time, and constitutional ability to convert biologically harmless nitrogen gas into plant-accessible soluble nitrogenous derivatives through nitrogen fixation, carbon dioxide sequestration, and phosphorous and potassium accessibilities. Algal biomass is therefore a highly attractive and demanding bioresource for sustainable green agricultural technology in the near future because to the previously mentioned naïve characteristics of algae, economic feasibility, technological acceptance, and environmental advantages. In order to satisfy the growing need for food supply, the current study

focuses on current trends and advancements in the development of biofertilizers based on algae and their powerful applications for improving current agricultural technology.

(Chaturvedi & Nikhil, 2016) [26] In addition to causing a fall in crop yield, fertility loss, and soil degradation, the ongoing increase in demand for food crops and productivity decline brought on by the ongoing use of chemical fertilisers has also taken us one step closer to attaining sustainable agriculture. By enhancing crop productivity via both nitrogen fixation and photosynthesis, algal biofertilizer offers an efficient, environmentally benign, and non-polluting method. Even when applied sparingly, algal biofertilizers enhance soil structure and boost yield productivity. When algal biofertilizers are applied to plants, the length of the roots and shoots increases along with the number of leaves, which boosts the plant's total growth. As one of the biggest producers and consumers of pulses, India has to produce a lot of pulses to meet the demands of its constantly expanding population. This may be done by employing algal bio-fertilizers. The use of algae biofertilizers as a crucial instrument for sustainability and an alternative to chemical fertilisers is briefly highlighted in this research.

6 METHODOLOGY

This review paper is based on a secondary research approach using previously published review articles, research papers and book chapters related to algae-based biofertilizers. Relevant literature was collected from online academic sources, including ScienceDirect, Springer, Frontiers, MDPI and Google Scholar. The selected studies focused on microalgae, macroalgae and cyanobacteria, with particular attention to their cultivation, production methods, agricultural applications and effects on soil fertility and crop growth. Information regarding nutrient availability, plant growth promotion, environmental benefits and production challenges was also examined. The findings from different studies were compared and organised according to the major themes of the review. This approach was used to understand the current developments, practical applications and limitations of algae-based biofertilizers in sustainable agriculture.

7 DISCUSSION

Taken together, the reviewed studies suggest that algae-based biofertilizers can raise agricultural productivity while easing some of the environmental damage that chemical fertilizers cause. Microalgae and cyanobacteria supply nutrients and growth-promoting compounds that benefit both plants and soil. Ghosh et al. (2022) and Chaturvedi and Nikhil (2016) presented algal biofertilizers as eco-friendly substitutes that can improve crop growth and lessen reliance on synthetic fertilizers. Ma et al. (2024) found that a microalgae-based biofertilizer increased hawthorn yield by 15.7–29.6% with no rise in overall greenhouse gas emissions intensity. Kumaran et al. (2026) further showed that pairing algal biofertilizers with biochar can improve soil pH, nutrient retention and microbial diversity. Even so, several issues limit practical use: production costs, biomass processing, poor storage stability and uneven performance in the field. Better cultivation methods, more suitable formulations and wider field trials are therefore needed to confirm how well these products work across different agricultural conditions.

8 CONCLUSION

Algae-based biofertilizers are a promising, environmentally friendly way to improve soil fertility, crop growth and the sustainability of farming. Microalgae, macroalgae and cyanobacteria release nutrients and bioactive compounds that help plants grow, make nutrients more available and improve soil conditions. Applied as seed treatments, soil amendments or foliar sprays, they can raise productivity and cut dependence on conventional chemical fertilizers. Growing algae on wastewater and agricultural residues adds another benefit, since it allows nutrients to be recycled and resources to be saved. Yet high production costs, difficult biomass harvesting, limited storage life and inconsistent field results continue to hold the field back. Future work should aim at cheaper cultivation systems, better product formulations and testing through large-scale field experiments. If these gaps are closed, algae-based biofertilizers could become a key part of sustainable agriculture and support more responsible crop production.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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