Research Article

Algae Biomass as Alternative Biofertilizers for Sustainable Agriculture and Soil Enhancement

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Abstract | Because of a sustained growth rate in population and anthropologic activities there is a growing need for sustainable and cost-effective farming practices to meet current and future food demands. Because soil is often low in available nutrients and there is an increasing demand to increases crops yields, the application of chemical fertilizers (nitrogen-based inorganic fertilizers) has intensified over recent decades. However, the excessive application of chemical fertilizers can result in environmental pollution and disturb local ecosystem, and sometimes cause crop decline gradually. Furthermore, their continuous overuse may ultimately contribute to nutrient imbalances and soil degradation. For these reasons, it was necessary to reassess many of the agricultural practices currently in place, including the use of chemical fertilizers, pesticides, herbicides and fungicides, and to provide solutions in a sustainable way.In this scenario, algal biomass emerges as a viable option. Algal biomass considered plant-beneficial soil conditioner, which contains significant amounts of growth hormone, polysaccharides, antibacterial material and other bioactive metabolites. known to enhance soil microbial activity, stimulate beneficial microorganisms, and improve nutrient cycling in eutrophic soils. This review examines the feasibility of using algal biomass as a biofertilizer, with emphasis on its potential roles in improving soil properties and supporting sustainable crop production. Furthermore, algal biomass can also be applied in industrial agricultural processes, particularly in wastewater treatment and carbon reduction, thereby contributing to sustainable agricultural development.

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Introduction

Modren agriculture must meet the growing demand for food and natural resources for human consumption. To achieve this, strategies that ensure high agricultural productivity and enhance the efficiency of the agricultural sector often rely on the intensive use of chemical fertilizers (Osorio-Reyes *et al*., 2023). Fertilizer are products that supply essential nutrients to plants and may originate from either organic or inorganic (synthetic) sources (Bhatt *et al*., 2019). Since their introduction in the mid - 20th century, chemical fertilizers have been extensively applied to maximize food production and sustain the food requirements of the global population.(Fasusi *et al.*, 2021)

Several chemical fertilizers containing nitrogen, phosphorus and potassium (NPK) are manufactured artificially and widely applied to arable land. However, excessive use deteriorate soil fertility and crop quality while contaminating air, water, and soil (Al-Sherif *et al.*, 2015; Das *et al.*, 2015; Cuellar-Bermudez *et al.*, 2017). Uncontrolled application contributes to soil acidification, depletion of essential cations, disruption of microbial biodiversity, and the release of toxic elements such as As, Cd, and Pb (Atafar *et al.*, 2010; Nosheen *et al.*, 2021). Too much reliance on N-rich fertilizers enhances these side effects, ending with ecosystem deterioration and emissions of greenhouse gases, eutrophication and soil degradation in long term (Osorio-Reyes *et al.*, 2023).

Several agroecological options have been developed to reduce the reliance on chemical fertilization. To this effect, biofertilizers have been demonstrated to be an efficient strategy to sustain crop productivity(Sumbul *et al.*, 2017). The growing attention on biofertilizers stems from the fact that they act as an organic substitute that alleviates several environmental issues associated to synthetic fertilizers (Arashiro *et al.*, 2018). Biofertilizers offers bioremediation to curb the loss of arable land and renew the fertility of degraded/barren soil in economic and environment sustainable ways(Osorio-Reyes *et al.*, 2023) . However, the sustainability and effectiveness of depend not only on crop yields, but also on improvements in soil health and functioning, particularly through positive effects on soil microbial communities There is also extensive evidence that crop rotations with legumes positively influence soil physicochemical and biological properties (Mitter *et al.*, 2021).

Biofertilisers are an eco-friendly substitute for chemical fertilizers to sustain the long term fertility of agricultural land, food production system etc. These biological inputs not only help to increase crop yield and quality but also improve plant stress tolerance, optimum use of essential nutrients such as phosphorus, nitrogen potassium and micro-nutrients,promote beneficial interactions with soil microbiome, provide protection from pathogenic toxicity etc (de Siqueira Castro *et al.*, 2020; Alvarez *et al.*, 2021). Of all types of biofertilizer, the ones derived from photosynthetic organisms (eukaryotic microalgae, anoxygenic phototrophs and cyanobacteria) are receiving an attention increase because their role in soil fertility maintenance and crop productivity enhancement is more specific (Thilagar *et al.*, 2016; Li *et al.*, 2017). They also demonstrated that green microalgae can be utilized as biofertilizer due to their potential supported by recent studies in promoting plant growth, improvement of fruit quality and nutritional value, soil fertility, and grain yield (Coppens *et al.*, 2016).

This review describes the microalgae as biofertilizers and their advantages over conventional chemicals fertilizers, transferred to crops and soil, referring preferentially to the environmental impact that these could cause compared with chemical fertilization s employed in intensive agricultural uses. The aim of this review is to underscore their support to sustainable agriculture and circular economy with a focus on protecting natural resources.

Functional characteristics of algal groups used as biofertilizers

This increasing recognition of the assemblage of services provided by algal-based fertilization has served to underscore its positive effects on crop yield, environmental quality and human health. sustainable use can significantly minimize reliance on chemical fertilizers, which alongside being effective in high yielding, exacerbate eventual loss of soil fertility. Additionally, utilization of alga biomass as biofertilizer contribute towards reduction in CO_2 emissions from agriculture without the further decrease of soil fertility. This dual advantage positions algal biofertilizer as a sustainable alternative that supports the achievement of agricultural industry goal while stimultaneosly promoting acircular bioeconomy with significant benefits for farming system,industry, and society as a whole (Osorio-Reyes *et al.*, 2023).

Microalgae represent a valuable component of algal biofertilizers due to their high contents of proteins, amino acids, vitamins, and essential macro- and micronutrients, in addition to a broad spectrum of bioactive metabolites, including antioxidants, polyunsaturated fatty acids, and carotenoids. Although nitrogen fixation is limited to specific taxa, most microalgal species enhance plant nutrition through biomass mineralization, leading to the gradual release of nitrogen and phosphorus and the production of growth-promoting compounds.

Their application improves soil organic matter and stimulates soil microbial activity via extracellular exudates, while microalgal extracts function as effective plant biostimulants that enhance physiological performance(Song *et al*., 2024). As living and adaptable organisms, microalgae can be optimized to suit different crop types releasing compounds that promote plant growth or alternatively, biopesticides that reduce losses and aid in pest control. This adaptability represents a key advantage of microalgae over conventional fertilizers (Osorio-Reyes *et al*., 2023).Cyanobacteria, particularly genera such as *Anabaena* and *Nostoc*, are distinguished by their capacity for biological nitrogen fixation mediated by specialized heterocyst cells, making them especially effective in flooded agroecosystems, including rice paddies. Beyond nitrogen inputs, cyanobacteria produce extracellular polymeric substances and synthesize phosphatases and organic acids that promote phosphorus solubilization through chelation and acidification, thereby improving soil aggregation, moisture retention, and microbial network stability following biomass decomposition (Miranda *et al*., 2024). In contrast,

Dried macroalgae are particularly characterizedby high concentrations of carbohydrates, such as mannan, ulvan, carrageenan, agar, laminarin, mannitol, alginate, fucoidin, fucose, and uronic acid, are what define the dehydrated macroalgae, soluble organic compounds, phytohormones such as auxins and cytokinins, and mineral elements including potassium and magnesium. When applied as foliar sprays or via irrigation, macroalgal products act as fast-acting biostimulants that enhance root architecture, nutrient uptake efficiency, and tolerance to abiotic stress. However, owing to their relatively low nitrogen and phosphorus contents, marine macroalgae are generally less suitable as direct nutrient sources and are more effectively utilized as biostimulant inputs rather than primary fertilizers (Chen *et al*., 2015; Mughunth *et al*., 2024).

Microalgae as biofertilizer

In order to improve the economic feasibility of microalgae technology, more research is required on nutrient optimization, agricultural applicability, water recycling, industrial scale harvesting and extraction side-product utilization. These developments are likely to widen the application spectrum for microalgae in environmentally relevant processes such as carbon dioxide sequestration and climate change mitigation according to international agreements (Osorio-Reyes *et al*., 2023) . Furthermore, these achievements have the potential to mitigate increasing demands for environmentally-friendly fertilizers and also facilitate greenhouse gases emission mitigation.

Micro-algae represent a group of microorganisms characterized by high contents of proteins, fats and vitamins in its biomass. As a result, microalgae provide other advantages in addition to being an alternative to traditional purification techniques (Markou and Georgakakis, 2011). When added to soil, microalgae mainly contribute their physical properties on the soil, provide essential biomaterials and enhance microbiological activity (Kalyanasundaram *et al*., 2020).

Microalgal biomass has become popular for use as bio-fertilizer because of its high content of plant hormones, biologically active substances and micro/macro elements, which in soil results in the improvement of soil biochemical properties interacting with microbiota (Marks *et al*., 2019). Similar to this, microalgae have high rates of absorption for nitrogen and phosphorus which means they are adapted organisms to grow in oligotrophic environment by efficiently incorporating nutrients into their metabolism (de Souza *et al*., 2019). The use of microalgae in soil is an environmentally friendly technology that enhances crop and soil health. The favorable soil related conditions such as suitable moisture, pH, and light can thrive the metabolic activity of viable microalgal cells which in turn stimulate atmospheric nitrogen fixation, nutrient availability, and development of symbiotic relationship with soil microbes/plant roots (de Souza *et al*., 2019).

Compared to other treatments, the combination of microalgae and terrestrial plants facilitated the greatest improvement in plant biomass, including significantly promoted foliage growth and branch development; all measurements of photosynthetic pigment showed that the plant was not stressed. Furthermore, microalgae can establish symbiotic relationships with bacteria to survive together in various habitats. This consortium shows a great promise for applications including feedstock preparation, nutrient retrieving, wastewater treatment as well as biofuels and biofertilizers (Aditya *et al*., 2022).

Microalgae have the potential to serve as biocontrol agents or as biopesticides due to their production of biocidal secondary compounds like benzoic acid and majusculonic acid, or hydrolytic enzymes with capacity to diminish the growth of fungi, bacteria, and nematodes (Renuka *et al*., 2018). The efficacy of microalgal biofertilizer on soil is influenced by the mode of application to soil and also by physiological nature of biomass either it is a fresh, dried or digested (de Souza *et al*., 2019).

Cyanobacteria-Based biofertilizers: Mechanisms, Benefits, and challenges

The high cost of chemical fertilizers has driven small-scale farmers to seek affordable and sustainable alternatives that maintain soil fertility, crop productivity, and agroecosystem health. Among these alternatives, cyanobacteria (blue-green algae) have emerged as one of the most promising biofertilizers due to their ability to biologically fix atmospheric nitrogen, produce organic biomass, and synthesize a wide range of beneficial metabolites. Cyanobacteria-based biofertilizers can significantly improve soil fertility and support sustainable crop yields, particularly in low-input farming systems (Pandey *et al*., 2020).

According to recent studies, nitrogen-fixing cyanobacteria convert atmospheric nitrogen (N_2) into bioavailable nitrogen, such as ammonia, by nitrogenase enzymes in heterocyst filamentous species. During biomass decomposition, they release additional growth-stimulating substances such as vitamins, peptides, and low molecular weight organic compounds, enriching the nitrogen content in the soil and improving its fertility and plant growth (Nawaz *et al*., 2025). In addition to enriching the soil with nitrogen, cyanobacteria contribute to the phosphorus cycle. Many strains are characterized by their ability to solubilize insoluble inorganic phosphates, such as ferric phosphate, aluminum phosphate, and hydroxyapatite, into soluble and plant-available phosphorus through mechanisms including organic acid production, chelation, and enzymatic solubilization, thus enhancing phosphorus availability in the soil. Some species, including *Nostoc carneum*, *N. piscinola*, *Anabaena torulosa*, and *Aulosira doliolum*, have demonstrated high phosphorus solubilization efficiency, reaching up to 80% under experimental conditions (Kollmen and Strieth, 2022).

Cyanobacteria also improve soil physical properties through the synthesis of extracellular polymeric substances (EPS), which act as natural binding agents that aggregate soil particles into stable filamentous networks. These EPS enhance soil aggregation, moisture retention, and resistance to erosion, creating a favorable microenvironment for root development and microbial activity (Zhang *et al*., 2024). Moreover, cyanobacteria and associated microalgae produce secondary metabolites, including phytohormones, polysaccharides, and bioactive compounds with antimicrobial properties, which indirectly stimulate plant growth, nutrient mobilization, and plant protection (Nichols *et al*., 2020)

Despite these advantages, the effectiveness of cyanobacteria-based biofertilizers is strongly influenced by environmental factors. Nitrogen fixation is highly sensitive to light intensity, oxygen concentration, temperature, and moisture availability, and suboptimal conditions can significantly reduce nitrogenase activity under field conditions (Nawaz *et al*., 2024; Wu *et al*., 2024). In addition, variability in cyanobacterial biomass production, nitrogen fixation rates, and metabolite release across different soils and climates remains poorly understood, leading to inconsistent biofertilizer performance.

Mechanisms of phosphorus solubilization and mobilization by cyanobacteria

Cyanobacteria enhance phosphorus availability in soils and aquatic systems through several complementary biochemical and physiological mechanisms, which can be summarized as follows:

Chelation-mediated dissolution of phosphate minerals

Cyanobacteria produce extracellular chelating agents capable of binding divalent cations, particularly Ca^{2+}, associated with insoluble phosphate minerals such as hydroxyapatite. This chelation process facilitates the release of phosphate ions into the surrounding medium without causing significant changes in pH (Roychoudhury and Kaushik, 1989):

$$Ca_{10}(OH)_2(PO4)_6 \rightarrow 10Ca^{+2} + 2OH^- + 6PO4^{-3}$$

This mechanism is particularly important in calcareous soils where calcium-bound phosphates predominate.

Organic acid production and acid-mediated solubilization

Cyanobacteria excrete low-molecular-weight organic acids, such as carbonic acid, as metabolic by-products. These acids contribute to the solubilization of insoluble phosphate compounds by proton substitution and complexation reactions, thereby enhancing phosphate bioavailability (Bose and Nagpal, 1971):

$$Ca_3(PO4)_2 + 2H2CO_3 \rightarrow 2H_2CaHPO_4 + Ca(HCO_3)_2$$

Mineralization upon cell death

During growth, cyanobacteria assimilate organic phosphorus compounds into their biomass. Upon cell senescence and death, microbial degradation and mineralization processes convert these organic forms into inorganic orthophosphate (PO_4^{3-}), which is subsequently released into the soil or aquatic environment. This mechanism sustains microbial nutrient cycling and significantly enhances phosphorus availability for plants and other organisms (Mandal *et al*., 1999).

Through these mechanisms, cyanobacteria significantly enhance phosphorus cycling in soils, thereby reducing dependence on synthetic phosphate fertilizers and promoting sustainable agriculture.

Early observation by Fuller and Rogers (Fuller and Rogers, 1952) demonstrated that plants exhibit greater phosphorus uptake from algal sources compared to an equivalent supply of inorganic phosphate applied over the same period. This finding led to the hypothesis that cyanobacteria can absorb excess phosphorus from their surrounding environment and incorporate it into their cellular components, thereby concentrating the available phosphorus. Upon cell death, this stored phosphorus is gradually released into the soil through processes such as secretion, autolysis, or microbial decomposition, ultimately making it accessible to neighboring plants.

Historically, cyanobacteria biofertilizers particularly heterocystous nitrogen-fixing strains was largely restricted to rice cultivation. However, research over the past two decades has demonstrated their potential in a wide range of cropping systems. Both heterocystous and non-heterocystous forms of cyanobacteria, either alone or in combination with agriculturally beneficial green algae, bacteria, and fungi, have yielded promising results beyond rice cultivation (Prasanna *et al*., 2013) .

Multiple studies have shown that cyanobacteria can be effectively introduced into soil through various methods, including seed treatment, direct field application, irrigation with biofertilizer suspensions, and seed coating. These practices have been reported to enhance seed germination, radicle and coleoptile development, plant growth, and overall crop productivity in cereals, horticultural crops, and even commercial orchards. For example, cyanobacterial strains such as *Nostoc*, *Calothrix ghosi*, and *Hapalosiphon intricatus* have been isolated from the wheat rhizosphere and are known to stimulate early seedling growth and development.

Furthermore, biofertilizers formulated from synergistic associations of cyanobacteria and eubacteria enhance nutrient availability in the soil more efficiently and at a lower cost than synthetic fertilizers, offering a sustainable alternative for modern agriculture (Prasanna *et al*., 2013).

Most previous studies have emphasized on the N2-fixing capacity of diazotrophic cyanobacteria (Kaushik, 1998), but other potential benefits were relatively not well documented (Mandal *et al*., 1999). However, in recent years, the studies have shown that inoculation with cyanobacteria increased not only nitrogen but also other macro and micronutrient availabilities such as carbon (C), phosphorus (P), potassium (K) and zinc (Zn), bioavailability in soil and also their mobilization from soil to plant tissues and grains (Coppens *et al*., 2016) (Table 1).

Cyanobacteria for rice cultivation In various countries including Vietnam, China and India, cyanobacteria have been largely used in rice field as substitute nitrogen fertilizers. N. fixation and soil nitrogen availability are increased in plants fertilized with cyanobacterial biomass. Additionally, cyanobacteria are found to improve not only nitrogen but also phosphorus availability for balanced nutrient supply of crop growth and productivity (Odegard and Van der Voet, 2014).

Spirulina has also been advocated as a good protein resource in animal feed and an alternative to synthetic fertilizers for sustainable agriculture (Ahsan *et al*., 2008).

Application strategies and functional forms of algal biofertilizers in sustainable agriculture

Algal biofertilizers are promising tools for supporting

Table 1: *Applications of cyanobacteria and microalgae as biofertilizers: contributions, and modes of action.*

Crop / System	Cyanobacteria / Microalgae Used	Contribution / Benefit	Mode of Action	Reference
Rice (Japan, >40 varieties)	Blue-green algal fertilizer	Significant gains in rice yield	Biological N_2 fixation and soil nutrient enrichment	(Science/Ciencia-Watanabe *et al.*, 1951)
Various applications	*Spirulina platensis* (filamentous cyanobacterium)	Used as dietary supplement due to high protein and nutritional value	Grows in alkaline environments preventing contamination; suitable for environmental applications	(Olguín *et al.*, 1997)
Rice soils (Philippines, Malaysia, Portugal, India)	*Nostoc*, *Anabaena*, *Calothrix* (heterocystous forms)	Predominant diazotrophic genera contributing to soil fertility	Atmospheric N_2 fixation, soil aggregation	(Roger *et al.*, 1987)
Rice fields	Free-living cyanobacteria	Contribute 20–30 kg N/ha through nitrogen fixation	Biological N_2 fixation via nitrogenase	(Vaishampayan *et al.*, 2001)
Rice fields	*Azolla–Anabaena* symbiosis	Up to 600 kg N/ha nitrogen contribution	Symbiotic N_2 fixation (heterocystous *Anabaena*)	(Vaishampayan *et al.*, 2001)
Rice fields (Asia)	Various cyanobacteria	Used as biofertilizers replacing synthetic nitrogen fertilizers	N_2 fixation, phosphate solubilization	(Rai *et al.*, 2019)
Tomato cultivation	Bacterial–microalgal flakes + *Nannochloropsis* sp.	Increased carotenoid and sugar content	Photosynthesis-derived metabolites, secondary metabolites	(Coppens *et al.*, 2016)
Date palm cultivation	Green microalgae *Tetraselmis* sp.	Improved growth rate, 100% survival, enhanced root, leaf, and stem development	Growth-promoting hormones, improved nutrient uptake	(Saadaoui *et al.*, 2019)
Rice (Iran)	Cyanobacteria treatment of rice seeds	Faster germination compared to control	Growth-promoting metabolites and improved nutrient availability	(Saadatnia and Riahi, 2009)
Rice (India)	Blue-green algae (cyanobacteria) biofertilizer	Significant increase in rice plant size	Nitrogen fixation and soil fertility improvement	(Tripathi *et al.*, 2008)

sustainable agriculture due to their diverse forms and flexible application methods. They can be applied directly to the soil as fresh or dried biomass, increasing organic matter, promoting microbial diversity and activity, and improving nutrient availability, which positively impacts soil fertility and structure. Algal biofertilizers are also used as foliar sprays, a method that allows for the rapid absorption of nutrients and bioactive compounds, stimulating photosynthesis, increasing chlorophyll production, and activating metabolic processes in plants. Furthermore, seeds can be treated by coating or soaking them in algal suspensions before planting. This treatment improves germination rates, promotes early root development, and increases seedling vigor and resistance to environmental stresses, thanks to the plant hormones produced by the algae. Application with irrigation water or in flooded fields, especially in rice cultivation, is a common method that relies on cyanobacteria such as *Anabaena* and *Nostoc*, due to their ability to fix atmospheric nitrogen and make it available to the plant within the soil(Bahmani Jafarlou *et al.*, 2021; Parmar *et al.*, 2023; Jurado-Flores *et al.*, 2025; Rahman *et al.*, 2025).

The choice of application method depends on the form of the algal material, the crop type, and the plant's physiological stage. Fresh algae, particularly cyanobacteria, contain living cells capable of nitrogen fixation and activating soil microorganisms. However, their use remains limited to agricultural systems close to production sites due to their short shelf life and the difficulty of transporting them (Singh *et al.*, 2016; Joshi *et al.*, 2020). In contrast, dried algal biomass is stable, easy to store and transport, and is commonly used as an organic fertilizer that gradually releases nutrients, improving soil physical properties and increasing organic content, although its effect is slower compared to other forms(Górka *et al.*, 2018; Ronga *et al.*, 2019). Algal extracts, whether derived from microalgae or marine algae, are among the most commonly used forms for foliar spraying or irrigation. They are characterized by their rapid action due to their content of bioactive compounds such as auxins, cytokinins, vitamins, and micronutrients, which promote plant growth and improve plant resilience to environmental stresses. However, their direct impact on improving soil properties remains limited (Michalak and Chojnacka, 2015; Ali *et al*., 2021). Recent developments include the immobilized algae in materials such as alginate granules, biochar, or polymer carriers. This technique improves algal survival, prolongs nutrient release, and enhances field performance, particularly in dry and saline soils (Mallick, 2002). Consequently, recent studies confirm that combining fresh, dried, and extracted forms is an effective strategy for maximizing the efficiency of algal biofertilizers and achieving sustainable agricultural production while reducing reliance on chemical fertilizers.

Wastwater treatment and circular bioeconomy

Industrial wastewater is a significant cause of environmental contamination, but it contains high concentrations of nutrients and it can be used as culture medium for microalgae (Ahmed *et al*., 2021), Microalgae play a productive role in the circular bioeconomy, such as carbon sequestration, wastewater treatment and the production of food, energy, pharmaceuticals cosmetics and biofertilizers (Moreira *et al*., 2023). The development of microalgae in wastewater reduces cost associated with waste to energy and allows for the production of biomass that could have multiple uses (Ekinci *et al*., 2019). Such biomass can be directly used as biofertilizer and the treated water can also be reused for crop irrigation (Veronesi *et al*., 2015). It has been demonstrated that the algal biomass could stimulate plant growth, and increase the crops yields (Khan *et al*., 2009; Michalak and Chojnacka, 2015), showing its potential as an alternative fertilizer in sustainable agriculture.

The use of recycled materials as a culture medium is consistent with the circular economy concept and ensures broader use of microalgae. This synergetic application not only supports CO_2 and waste treatment, but also allows biofertilizer production, resulting in a more sustainable and economically practiced microalgal culture (Vázquez-Romero *et al*., 2022).

Microalgae can thus be produced in wastewater using flue gases, leading to wastewater treatment, CO_2 sequestration, and biomass production (Nayak *et al*., 2016). The use of waste resources greatly reduces the costs of algal biomass production (Almomani *et al*., 2019). Schreiber *et al*.(Schreiber *et al*., 2018) demonstrated that growing microalgae in polluted water bodies and then using the biomass obtained in food or agriculture will change pollutions of phosphor(P) in the direction. To do this, they compared the effect of microalgal live and dray biomass with chemical fertilizers on the availability of phosphorus and wheat growth. The plant performance observed differences between mineral fertilization and algal one were not recorded. The measured nitrogen and phosphorus uptake was virtually identical, though P was slightly lower, and the root length stomata was the same (Osorio-Reyes *et al*., 2023).

Wastewaters may have high concentrations of organic/inorganic nutrients, which are suitable for microalgae cultivation and then microalgae can rapidly produce biomass by assimilating these nutrients for the valuable biomolecules (Ummalyma *et al*., 2023). ntensive studies have been conducted on the applicability of microalgal production on removal of pollutants from different types of waste water such as municipal (Buitrón and Coronado-Apodaca, 2022), industrial (Vital-Jácome *et al*., 2020), and agricultural effluents (Wang *et al*., 2016; Li *et al*., 2019).

The growth of microalgae in wastewater has several advantages such as pollutant removal, organic matter oxidation and production of water (Kumar *et al*., 2022). Algal One well studied approach is algal remediation for treating aquaculture effluents to remove nutrients (Abreu *et al*., 2011; Lawton *et al*., 2013). The appropriate choice of algal species is critical for nutrient removal (which in turn determines the potential end uses of the produced biomass) (Wuang *et al*., 2016). However, there is no clear financial viability of growing microalgae for biofertilizer production alone. Vázquez-Romero *et al*. (Vázquez-Romero *et al*., 2022) explored the potential of microalgae biorefineries, including different production, harvesting and drying processes.

Phytohormons in algae or growth-promoting compounds

Microalgae have garnered increasing attention for their ability to produce plant hormones that play crucial roles in plant growth and development, organogenesis, and root and stem formation (Uniyal *et al*., 2022). This gives them a clear advantage over conventional fertilizers as natural plant stimulants (Ali *et al*., 2021). These hormones, present in algal extracts at nanogram-per-gram levels, include auxins, cytokinins, gibberellins, and abscisic acid, as well as vitamins (especially B vitamins), amino acids, antibiotics, and toxins (Lu and Xu, 2015; Mohamed *et al*., 2021). For example, cyanobacteria, such as *Arthrospira platensis*, have also been reported to produce gibberellins, plant hormones involved in fruit development, stem elongation, leaf unfolding, early flowering, sexual differentiation, and seed germination (Han *et al*., 2018). Certain free-living or symbiotic cyanobacteria, such as *Chlorogloeopsis*, *Plectonema*, *Anabaena*, *Nostoc*, and *Anabaenopsis,* enhance nutrient availability and indole-3-acetic acid (IAA) synthesis, significantly promoting plant growth and development (Natarajan *et al*., 2012). *Phormidium* strains SM-14 and SM-15 have been identified as IAA producers, while *Anabaena vaginicola* and *Nostoc calciola* have been shown to release several auxins (indole-3-acetic acid and indole-3-butyric acid) that stimulate wheat growth (Mazhar and Hasnain, 2011).

Researchers have demonstrated that ethylene is responsible for fruit ripening, controls germination, flowering, senescence, and fruit drop, and stimulates bacterial responses to biotic and abiotic factors. On the other hand, abscisic acid (ABA) is a key hormone in the stress response and is associated with seed dormancy and drought tolerance. In general, the use of algal-derived plant hormones has shown positive effects on germination, root and stem growth, biomass accumulation, leaf formation, and flowering characteristics (Iqbal *et al*., 2017).

Several studies have shown that treating plants with microalgae leads to increased accumulation of minerals, proteins, pigments, essential oils, plant hormones, and carbohydrates, as well as enhanced tolerance to abiotic stress. These data clearly indicate the role of microalgae as plant growth promoters (Osorio-Reyes *et al*., 2023). Beneficial effects have been reported in rice (Obreht *et al*., 1993), wheat (Gantar *et al*., 1995; Nain *et al*., 2010), and various vegetables such as squash, tomatoes, and cucumbers (Shariatmadari *et al*., 2013). More recently, Tejada-Ruiz *et al*. (2020) reported that foliar spraying of an aqueous solution extracted from *Arthrospira platensis* algae, supplemented with plant hormones (cytokinins, gibberellins, salicylic acid, abscisic acid, indoleacetic acid, and jasmonic acid) with potassium silicate, stimulated the growth and flowering of *Pelargonium hortorum*.

Main risks associated with algal biofertilizers

Due to their high capacity for bioaccumulating dissolved elements and nutrients from surrounding environments, algae can absorb and concentrate trace elements such as cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As). When contaminated algal biomass is applied as a biofertilizer, these potentially toxic elements may accumulate in the soil and, depending on their chemical speciation, mobility, and bioavailability, may subsequently be taken up by crops or persist in the environment (Sarma *et al*., 2024).

Seaweeds, in particular, may contain elevated concentrations of iodine and, in some cases, arsenic—elements identified by the World Health Organization as contaminants of concern in seaweed-derived products. Consequently, the agricultural use of seaweed-based fertilizers may increase the risk of excessive exposure to these elements if raw materials and final products are not adequately monitored and regulated (PROGRAMME, 2025).

In addition, certain cyanobacterial species are known to produce toxic secondary metabolites, including hepatotoxins (e.g., microcystins), neurotoxins (e.g., anatoxin-A), cylindrospermopsin, and other bioactive compounds. If biomass derived from toxin-producing cyanobacteria is used as fertilizer, these toxins may persist in soils or be absorbed by crops, thereby posing potential risks to food safety and livestock health (Ramakrishnan *et al*., 2023).

Furthermore, algal biomass cultivated using wastewater may contain residual contaminants such as pharmaceuticals, pesticides, pathogenic microorganisms, or antibiotic-resistant bacteria. In the absence of appropriate treatment and quality control, these contaminants may be transferred to agricultural soils and crops. Therefore, when algal biomass is intended for use as a fertilizer in food production systems, it is essential to utilize clean water sources and well-characterized growth substrates, such as uncontaminated seawater, controlled freshwater systems, or defined culture media. Biomass produced from wastewater should be restricted to non-food agricultural or industrial applications (Sarma *et al*., 2024).

Risk mitigation strategies include the selection of algal species or strains with low tendencies to accumulate harmful elements and the exclusion of toxin-producing taxa. Additionally, toxin levels can be reduced through appropriate processing techniques, such as advanced oxidation processes, controlled thermal treatments, or enzymatic and biological degradation methods. These measures are critical to ensuring the safe and sustainable application of algal biofertilizers in agriculture (Rahman *et al*., 2025).

Conclusions and Recommendations

The incorporation of algal biomass in the form of a biofertilizer has good potential for sustainable substitution to chemical fertilizers, with increased soil fertility, crop yields and natural protection against plant diseases. At the same time, it is involved in the environmental management by nutrienexchange, wastewater treatment and carbon retention thus potentially minimizing both agriculture and industry CO 2. Such a technology has yet to be widely accepted due to economical and technical limitations. Further advancement in biotechnology, economic production and standardised modes of application will be required to develop algae as biofertilizer into a viable and environmentally safe alternative for modern agriculture.

Novelty Statement

This research is distinguished by providing a comprehensive critical and systematic analysis of the use of algal biomass as an alternative biofertilizer, through the development of a conceptual framework that links the mechanisms of algal action with the improvement of soil properties and the sustainability of agricultural systems, while highlighting research gaps and future trends in light of environmental challenges and climate change.

Generative AI or AI assisted technology statement
The authors declare that no genrative AI was used in the creation of this manuscript.

Conflict of interest
The authors have no conflict of interest.

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