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Harnessing Microalgae for Sustainable Agriculture

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This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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Abstract

Modern agriculture requires approaches that sustain crop productivity while reducing environmental burdens associated with intensive synthetic inputs. This review examines microalgae as multifunctional biological resources for sustainable agriculture, with emphasis on their roles as biofertilisers, biostimulants, biopesticides, soil amendments, and agents of bioremediation. Microalgal and cyanobacterial biomass can contribute to nutrient availability through biological nitrogen fixation, phosphorus and potassium mobilisation, and the delivery of macro- and micronutrients. Their metabolites, including phytohormones, polysaccharides, amino acids, vitamins, and antioxidant compounds, can support plant growth and stress responses. Microalgae also produce bioactive substances with potential applications in disease, insect, nematode, and weed management. In soils, microalgal biomass and exopolysaccharides can support aggregation, moisture retention, organic carbon inputs, and microbial activity, while microalgae-derived biochar provides an additional soil-amendment option. Microalgal systems may also assist in the removal of nutrients, heavy metals, and selected organic pollutants from contaminated soils and agricultural wastewater, with treated effluents and residual biomass offering opportunities for resource recycling. Open raceway ponds and closed photobioreactors provide contrasting production options, although large-scale cultivation costs, formulation stability, and variable field performance remain important constraints. Overall, the reviewed evidence supports the integration of microalgal technologies within circular agricultural systems, while further work is needed to improve production efficiency, application consistency, and practical scalability.

Keywords: Biofertiliser; biopesticide; bioremediation; microalgae; soil amendments.

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1. Introduction

Modern agriculture faces the critical challenge of increasing crop yields while safeguarding the environment to ensure long-term global sustainability. Although synthetic fertilisers and high-yielding crop varieties have historically expanded the global food supply, a continuous reliance on these hazardous chemicals prioritises immediate yields at the expense of ecosystem health (Chittora *et al.*, 2023; Ahmad Kamal *et al.*, 2024). Consequently, sustainable farming frameworks urgently require renewable, biologically derived alternatives to contribute to integrated nutrient management (Çakirsoy *et al.*, 2022).

Microalgae, photosynthetic microorganisms, offer a viable and elegant multi-functional solution through biological carbon capture, serving as sustainable biofertilisers, biostimulants, and biodegradable bioprotectants that support a circular bioeconomy (Kabato *et al.*, 2025). Recent studies further indicate that edaphic microalgae can contribute to soil aggregation, nutrient cycling, and carbon sequestration, supporting their consideration in climate-smart agricultural systems (Swami *et al.*, 2025). Cyanobacteria can also contribute to agricultural nutrient management through biological nitrogen fixation, including heterocyst-associated nitrogenase activity in nitrogen-fixing taxa (Pandey & Shallu, 2020). Recent syntheses describe microalgal bioinputs as multifunctional tools that combine soil conditioning, plant biostimulation, nutrient recycling, and phycoremediation, while continuing to identify production cost and scale-up as important implementation constraints (da Gama *et al.*, 2025; Nur *et al.*, 2025; Wang *et al.*, 2026). However, the evidence addressed across this field remains distributed among biomass production, nutrient mobilisation, biostimulation, biopesticidal activity, soil amendment, and bioremediation, creating a need for an integrated synthesis that connects these functions within a single sustainable-agriculture framework. This review explores the potential and strategic integration of microalgae into modern agricultural systems to sustain crop productivity while concurrently alleviating the ecological degradation driven by the intensive use of synthetic agro-inputs.

2. Characteristics of Microalgae

Microalgae comprise a diverse group of photosynthetic microorganisms, encompassing both eukaryotic protists such as green algae (division Chlorophyta), diatoms (class Bacillariophyceae), euglenoids (class Euglenophyceae), and dinoflagellates (division Dinophyta), and prokaryotic cyanobacteria (divisions Cyanophyta and Prochlorophyta). These organisms exist either as solitary unicellular forms or as simple multicellular assemblies, with cellular dimensions typically spanning from 1 to 400 µm (Alvarez *et al.*, 2021; Bossa *et al.*, 2024). Due to their remarkably broad physiological tolerance to fluctuations in salinity, temperature, and pH, microalgae successfully colonise a vast spectrum of ecological niches, including aquatic, terrestrial, and subaerial habitats (Alvarez *et al.*, 2021; Reza-Solis *et al.*, 2023).

Functionally, most microalgae operate as photoautotrophs, utilising a photosynthetic apparatus similar to that of higher plants to convert solar energy into chemical energy (Reza-Solis *et al.*, 2023). They possess minimal nutritional requirements for growth and development, occupy a small physical footprint, and can be easily cultivated at scale (Costa *et al.*, 2019). Throughout their active growth phases, distinct cellular metabolic pathways drive the synthesis and accumulation of an array of complex molecules. Consequently, microalgae serve as a prolific bio-resource for both primary and secondary metabolites, which are synthesised and sequentially exuded at specific stages of their physiological life cycle (Lam *et al.*, 2012).

3. Microalgal Biomass Production

Microalgal cultivation functions as an efficient bioremediation and carbon-capture method, reducing global warming by capturing atmospheric carbon dioxide (CO_2) (Kazbar *et al.*, 2019). Utilising nutrient-dense municipal and industrial wastewater as a cultivation medium economically optimises large-scale biomass production (Ummalyma *et al.*, 2023; Osorio-Reyes *et al.*, 2023). This strategy lowers the cost of nutrient supplies while simultaneously purifying polluted water systems. Currently, microalgal production is mainly carried out in either open raceway ponds (ORPs) or closed photobioreactors (PBRs).

3.1 Microalgal Biomass Production Methods

3.1.1 Open Raceway Ponds (ORPs)

Open raceway ponds (ORPs) are the most widely used commercial systems for large-scale microalgal farming because they are simple to operate and highly cost-effective (Ryu *et al.*, 2019). These shallow outdoor pools are usually kept at a depth of about 30 cm and use a motorised paddle wheel to keep the mixture of cells, water, and nutrients constantly moving around a looped track (Karthikeyan *et al.*, 2016).

As they rely entirely on natural sunlight, ORPs require much lower initial setup and daily operating expenses than closed systems. However, their open-air design creates significant environmental and biological challenges. ORPs suffer from heavy water loss through evaporation and poor temperature control, causing erratic changes in the growing environment. Additionally, exposure to the atmosphere creates a high risk of contamination from competing or predatory microbes, which severely limits the specific types of microalgae that can be successfully grown (Cenciani *et al.*, 2011; Udayan *et al.*, 2022).

3.1.2 Closed Photobioreactors (PBRs)

Photobioreactors use enclosed, engineered designs made from transparent materials such as glass, acrylic, or polycarbonate to eliminate the environmental risks of open ponds. PBRs enable precise management of crucial growing conditions, such as pH, temperature, light levels, and nutrient feeds (Cenciani *et al.*, 2011). Modern advancements also include PBRs with self-forming dynamic membranes that allow for simultaneous biomass growth and automated harvesting (Senatore *et al.*, 2022).

By preventing contamination, PBRs are ideal for maintaining pure monocultures and producing high-value bioproducts such as specialised pigments (carotenoids and xanthophylls), pure proteins, and polyunsaturated fatty acids (Manu *et al.*, 2024). The main disadvantage of closed PBRs is their higher installation, engineering, and operational costs compared to ORPs (Cenciani *et al.*, 2011).

3.2 Phases of Microalgal Biomass Production

The core steps involved in microalgal biomass production are: (a) strain selection and inoculum preparation, (b) cultivation system setup, (c) harvesting, (d) drying and stabilisation, and (e) extraction and downstream processing (Singh *et al.*, 2025). Downstream processing is used to turn liquid microalgae cultures into solids. This step usually accounts for 20–30% of the total production cost (Silva & Silva, 2013). Methods used in downstream processing include centrifugation, drum drying, and lyophilisation (freeze-drying) to obtain a solid form of the algae (Ronga *et al.*, 2019).

4. Application of Microalgae in Agriculture

Microalgae play a pivotal role in sustainable agriculture, serving as multifunctional agents that enhance both soil and crop health (Parmar *et al.*, 2023; Song *et al.*, 2022).

4.1 Microalgae as Biofertiliser

Microalgae-based biofertilisers consist of formulations containing either active algal biomass or viable cells. When inoculated into the plant-soil system, they augment nutrient availability and stimulate crop productivity (Parmar *et al.*, 2023). Rich in proteins, amino acids, lipids, polysaccharides, vitamins, and minerals, this biomass delivers essential macro- and micronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K) (Sarkar *et al.*, 2023). The primary and most widespread agricultural application of microalgae is their deployment as functional biofertilisers (Gonçalves, 2021).

4.1.1 Nitrogen Fixation

Nitrogen fixation is the second most vital process in crop production after photosynthesis. Cyanobacteria enhance soil fertility by transforming inert atmospheric nitrogen (N_2) into plant-absorbable ammonium (NH_4) (Alvarez *et al.*, 2021). However, the driving nitrogenase enzyme complex is highly oxygen-sensitive, requiring specialised evolutionary strategies to overcome the oxygen paradox during oxygenic photosynthesis (Stal, 2015). Cyanobacteria manage this through three distinct mechanisms: spatial separation, where heterocystous strains (e.g., *Anabaena* spp.) isolate nitrogenase inside thick-walled heterocysts; temporal separation, where non-heterocystous strains (e.g., *Lyngbya* spp.) photosynthesise by day and fix nitrogen by night; or a sophisticated combination of both spatial and temporal separation (e.g., *Trichodesmium* spp.) (Issa *et al.*, 2014).

Biological nitrogen fixation is highly optimised through cyanobacterial applications, notably in the *Azolla-Anabaena* symbiosis, which fixes 20–30 kg N ha^{-1} and significantly enhances rice nitrogen uptake (Bhuvaneshwari & Singh, 2015). Similarly, free-living consortia (e.g., *Nostoc entophytum* and *Oscillatoria angustissima*) boost crop growth and germination by combining direct nitrogen fixation with elevated endogenous nitrate reductase activity (Osman *et al.*, 2010). Conversely, while non-fixing eukaryotic microalgae (e.g., *Chlorella*, *Scenedesmus*, *Nannochloropsis*) lack nitrogenase complexes, they function as high-efficiency, slow-release organic fertilisers. These matrices gradually mineralise organic nitrogen (demonstrating rates of 25-31%), which effectively prevents nutrient leaching while accelerating early seedling development and matching the biomass yields of full synthetic fertilisation regimes (Pérez *et al.*, 2023).

4.2 Phosphorus Solubilisation and Mobilisation

Soil phosphorus predominantly exists in insoluble inorganic (e.g., apatite) or organic complexes (e.g., inositol phosphates, phosphomonoesters, and phosphotriesters), limiting plant accessibility (Mahanty *et al.*, 2017). Phosphate-solubilising microorganisms (PSMs), including specific microalgae, efficiently mobilise these fixed pools, delivering up to eight times more bioavailable phosphorus than conventional chemical alternatives and boosting crop P uptake by 3- to 4.4-fold (Bossa *et al.*, 2024; Kabato *et al.*, 2025). This mobilisation is driven by distinct mechanisms: microalgae exude organic acids to lower rhizosphere pH or utilise photosynthetic CO_2 fixation to raise it, dissolving inorganic complexes and calcium-bound phosphates (Sun *et al.*, 2026). Concurrently, they secrete extracellular enzymes to mineralise organic phosphorus compounds (Markou *et al.*, 2014). Furthermore, microalgae optimise internal nutrient efficiency via "luxury uptake" polyphosphate storage and establish mutualistic consortia with native soil PSMs to accelerate overall nutrient cycling (Çakirsoy *et al.*, 2022; Sun *et al.*, 2026).

4.3 Potassium Solubilisation and Mobilisation

Despite its abundance, 90–98% of soil potassium is sequestered within insoluble mineral matrices like feldspar, mica, and illite, making it inaccessible for direct plant uptake (Sattar *et al.*, 2019). Microalgal biofertilisers have emerged as a sustainable strategy to mobilise these mineral reserves. The potassium content varies significantly across microalgal species; for instance, *Phaeodactylum tricornutum* accumulates the highest K content at 2.4% w/w, while other common strains range between 0.7% and 1.8% w/w (Parmar *et al.*, 2023). Foliar application of *Arthrospira* and *Scenedesmus* extracts elevated K content by 12% and 10%, respectively, in *Petunia × hybrida* compared to untreated controls (Plaza *et al.*, 2018).

4.4 Bioavailability of other Macro and Micronutrients

Microalgae serve as biogenic reservoirs for secondary macronutrients and trace elements, with their agronomic efficacy determined by growth phase and biochemical composition (Parmar *et al.*, 2023). Microalgal filtrates significantly enhance crop biomass and mineral uptake through the synchronised release of soluble nutrients and extracellular signalling compounds (Kholssi *et al.*, 2019). During the active growth phase, microalgae accumulate higher concentrations of proteins, amino acids (arginine, histidine, ornithine), and key minerals (Mg, Mn, Fe, Zn) compared to the stationary phase (Sandgruber *et al.*, 2023). To counteract iron deficiency in aerated soils with a pH above 7.0, microalgae secrete low-molecular-weight siderophores that chelate and solubilise fixed Fe^{3+} ions for plant assimilation (Parmar *et al.*, 2023). Additionally, while standard cellular calcium ranges from 0.1% to 2.9% w/w, specific species such as *Tetraselmis chuii* (2.99% w/w) and *Phaeodactylum tricornutum* (2.91% w/w) exhibit notable hyper-accumulation traits, enhancing their utility as functional biofertilisers (Di Lena *et al.*, 2020).

5. Microalgae as Biostimulants

Microalgae synthesise a diverse array of biologically active compounds, including phytohormones, amino acids, polypeptides, functional polysaccharides, phenolics, terpenoids, and extracellular polymeric substances (EPS) that enhance crop productivity by optimising nutrient assimilation pathways and fortifying plant defence mechanisms (Gonçalves, 2021; Parmar *et al.*, 2023). Due to this inherent biostimulatory efficacy, several prominent microalgal genera, such as *Chlorella* spp., *Arthrospira platensis* (Spirulina), *Acutodesmus* spp., *Scenedesmus* spp., *Dunaliella* spp., and *Calothrix elenkinii*, have been extensively commercialised as agricultural biostimulants to improve overall crop performance and agroecological resilience (Ronga *et al.*, 2019; Colla & Rouphael, 2020).

5.1 Phytohormones

Microalgae possess the endogenous capacity to biosynthesise a complex network of primary plant growth regulators including auxins, cytokinins, gibberellins, ethylene, brassinosteroids, and defence elicitors (salicylic and jasmonic acids), making them potent agricultural biostimulants (Tarakhovskaya *et al.*, 2007; Kapoore *et al.*, 2021). Biochemically, these phytohormones modulate critical physiological processes: initiating seed germination, promoting cellular elongation in roots and shoots, and enhancing antioxidant systems to mitigate environmental stress (Chabili *et al.*, 2024). The phytohormone content in microalgal biomass is highly dependent on the specific genotype, cultivation dynamics, and extraction methods (Plaza *et al.*, 2018).

Quantitative profiling shows significant strain-dependent variation, with indole-3-acetic acid (IAA) ranging from 0.18 to 99.83 nmol g^{-1} dry weight (DW) across various green microalgae, and brassinosteroids reaching up to 977.8 pg g^{-1} DW in charophytes (Stirk *et al.*, 2013; Kapoore *et al.*, 2021). Exogenous application of these microalgal and cyanobacterial extracts triggers major phenotypic improvements in crops; for instance, *Phormidium* strains accelerate wheat seedling root and shoot elongation by up to 21% through synergistic hormone action (Mazhar & Hasnain, 2011), while foliar applications of *Chlorella* sp. on tomato stimulate early flowering and increase both fruit size and total yield via codependent auxin and exopolysaccharide pathways (Gitau *et al.*, 2022). Volatile ethylene production is predominantly localised in cyanobacterial lineages, including *Synechococcus*, *Anabaena*, *Nostoc*, *Calothrix*, *Scytonema*, and *Cylindrospermum* (Lu & Xu, 2015).

5.2 Polysaccharides

Polysaccharides synthesised both intracellularly and extracellularly by eukaryotic microalgae, including *Chlorella* spp., *Porphyridium cruentum*, *Tetraselmis* spp., and *Dunaliella salina*, function as potent biostimulants and vital signalling ligands in plants (Chanda *et al.*, 2019; Moreira *et al.*, 2022). These carbohydrate polymers accelerate structural root development, enhance trace mineral bioavailability via natural chelation pathways, and improve photosynthetic efficiency by upregulating Rubisco synthesis. Furthermore, microalgal polysaccharides fortify crops against both biotic and abiotic stresses while mitigating oxidative damage by boosting endogenous antioxidant enzyme activities to actively neutralise reactive oxygen species (ROS) toxicity (Chanda *et al.*, 2019).

5.3 Other Bioactive Biostimulants

Microalgal biomass acts as a diverse repository of plant growth promoters (PGPs), including essential amino acids, vitamins, and antioxidants, that collectively optimise crop ontogeny, improve photosynthetic pathways, and delay leaf senescence (Chiaiese *et al.*, 2018; Chabili *et al.*, 2024). As bioavailable organic nitrogen sources, microalgae-derived free amino acids (such as tryptophan and arginine) serve as critical metabolic precursors for the biosynthesis of indole-3-acetic acid (IAA), salicylic acid, and polyamines, driving major vegetative and reproductive growth advancements across diverse crops like papaya, tomato, and squash (Chiaiese *et al.*, 2018; Guedes *et al.*, 2018). Concurrently, microalgae synthesise robust vitamin matrices—with high concentrations of vitamin C (up to 191 mg kg^{-1} in *Tetraselmis suecica*) and major B-complex vitamins (Edelmann *et al.*, 2019). When paired with primary antioxidant pigments (such as α-/β-carotene, fucoxanthin, phenolic acids, and flavonoids like kaempferol), these complexes act as natural photoprotective sunscreens that safeguard cellular machinery against oxidative stress and destructive UV-B radiation (Alemu & Roro, 2020; Sirohi *et al.*, 2022).

6. Microalgae as Biopesticides

Microalgae synthesise diverse allelopathic chemicals that function as potent algicides, fungicides, herbicides, insecticides, and nematicides (Alvarez *et al.*, 2021). Notably, microalgal species such as *Chlorella vulgaris*, *Chlorella fusca*, and *Scenedesmus* spp. have demonstrated significant biopesticidal activity (Bileva, 2013).

6.1 Disease Management

The extracellular metabolites of *Nostoc muscorum* and *Oscillatoria* sp. have reduced the mycelial growth of *Alternaria porri* by 20.37% and 36.34%, respectively, outperforming other tested cyanobacterial species such as *Anabaena oryzae*, *Arthrospira* sp., and *Nostoc minutum*. This pronounced fungicidal activity is primarily attributed to high concentrations of phenolic compounds and alkaloids within these two species (Abdel-Hafez *et al.*, 2015). Furthermore, species including *Anabaena laxa*, *Anabaena variabilis*, *Nostoc* spp., and *Calothrix elenkinii* synthesise cell wall–degrading enzymes, such as chitosanase, β-1,4-glucanase, and β-1,3-glucanase, which degrade the structural integrity of pathogens like *Pythium aphanidermatum* (Natarajan *et al.*, 2013).

Cyanobacteria secrete extracellular polysaccharides (EPS) and antimicrobial compounds that suppress pathogen growth. For instance, *Nostoc* spp. and *Nodularia harveyana* produce cyclic compounds, including 4,4′-dihydroxybiphenyl, norharmane, and diterpenoids, which exhibit robust antibacterial properties (Volk & Furkert, 2006). Beyond directly targeting fungal pathogens, microalgal and cyanobacterial extracts fortify endogenous plant defence mechanisms. They stimulate the activity of host hydrolytic enzymes, including endochitinases (β-N-acetylhexosaminidase, chitin-1,4-β-chitobiosidase, and endoglucanase β-1,3-glucanase), polyphenol oxidase, and peroxidase (POD) (Roberti *et al.*, 2015).

6.2 Insect Management

Cyanobacteria synthesise key secondary metabolites and enzymes, such as polyphenol oxidase, chitinase, and phenylalanine, which confer insecticidal properties (Renuka *et al.*, 2018). Additionally, cyanobacterial biofilms form a physical and biochemical protective barrier on plants against pest infestations (Thapa *et al.*, 2017). Microalgal biopesticides disrupt both the larval and adult stages of pests. This insecticidal action is driven by specific amines, sesquiterpenes, and alkaloids. For example, compounds isolated from the genus *Fischerella* include 12-epi-hapalindole C isonitrile and hapalindole (Hernández-Carlos & Gamboa-Angulo, 2011).

6.3 Nematode Management

Among these bioactive compounds, Anatoxin-A functions as a potent neurotoxin that binds irreversibly to acetylcholine receptors, inducing continuous muscle contractions that ultimately immobilise nematode pests (Mankiewicz *et al.*, 2003). Multiple cyanobacterial and microalgal species such as *Oscillatoria chlorina*, *Aulosira fertilissima*, *Spirulina platensis*, and *Amphora coffeaeformis* exhibit distinct nematicidal activity against destructive soil-borne nematodes, such as root-knot nematodes (*Meloidogyne arenaria*, *Meloidogyne incognita*) and *Xiphinema index* (Bileva, 2013).

Soil application of *Chlorella vulgaris* successfully suppresses nematode proliferation, mitigates root gall formation, and enhances overall root and shoot architecture. Similarly, microalgae-derived secondary metabolites, such as hexamethyl phenol, methoxyphenyl compounds, and flavonoids, inhibit nematode reproduction and decrease gall formation in *Cucumis sativus* roots, while concurrently boosting fruit yield and quality (El-Eslamboly *et al.*, 2019).

6.4 Weed Management

Microalgae hold immense potential for sustainable weed management due to their ability to exude allelochemicals that disrupt seed germination, root elongation, and critical physiological pathways in weed species. For example, extracts from *Chlorella vulgaris* inhibit the germination of specific grassy weeds, while metabolites synthesised by *Scenedesmus* species suppress the root growth of competing vegetation (Singh *et al.*, 2019).

Cyanobacteria such as *Anabaena* and *Nostoc* release allelopathic substances that effectively hinder the establishment of weed seedlings in rice fields (Casanova *et al.*, 2023). Consequently, microalgal allelochemicals serve as viable, eco-friendly alternatives to synthetic herbicides because they are rapidly biodegradable and minimise non-target toxicity in the environment (Casanova *et al.*, 2023).

7. Microalgae as Soil Amendments

Microalgae function as natural soil conditioners that improve the physical and chemical properties of agricultural lands by contributing substantial biomass and organic compounds to boost structure, moisture retention, and overall fertility (Osorio-Reyes *et al.*, 2023). Within edaphic microbial ecosystems, they represent a highly influential group, accounting for approximately 27% of the total microbial biomass and serving as sensitive bioindicators of land use (Grzesik & Romanowska-Duda, 2014; Abinandan *et al.*, 2019). Targeted inoculation with cyanobacterial genera such as *Nostoc* and *Anabaena* dynamically optimises nutrient balances and organic carbon content to elevate soil productivity (Singh *et al.*, 2016). Furthermore, during cellular growth and subsequent decomposition, microalgae release exopolysaccharides (EPSs) that expand soil organic carbon pools, yielding a readily available substrate that accelerates broader heterotrophic microbial proliferation (Tiwari *et al.*, 2019).

7.1 Microalgae-mediated Soil Aggregation

Microalgae-mediated soil aggregation is fundamental to optimising soil oxygen levels, structural porosity, and moisture retention dynamics (Song *et al.*, 2022). Following cell division, these microorganisms secrete sticky, mucilaginous sheaths that physically cement disparate soil particles into stable structural macrostructures. This biological binding significantly enhances pore space connectivity, which accelerates water infiltration rates, maximises water-holding capacity, and improves root-zone aeration. Consequently, the stabilised soil matrix displays robust resistance against both wind and water erosion, fostering efficient nutrient cycling and superior seed germination kinetics compared to individual unaggregated soil particles (Rossi & De Philippis, 2015).

7.2 Microalgal Exopolysaccharides (EPS) as Edaphic Modifiers

Microalgal exopolysaccharides (EPSs) released during cellular decomposition act as potent soil modifiers that elevate organic carbon pools and stimulate the metabolic activity of soil microbiota (Tiwari *et al.*, 2019). Biochemically, these biocompatible polymers physically cement loose soil particles to mitigate erosion, while cyanobacterial EPS fractions optimise macro-aggregation and water retention to enhance nutrient bioavailability and buffer excess salts in salinity-affected soils (Rossi & De Philippis, 2015). However, excessive EPS accumulation poses a distinct risk of bioclogging by obstructing soil pore networks, which severely suppresses porosity and hydraulic conductivity, a phenomenon highly pronounced in fine-textured clay substrates (Kabato *et al.*, 2025). To prevent detrimental compaction and overly dense aggregation within clay matrices, the co-incorporation of structural organic amendments, such as straw, is highly recommended during application (Kabato *et al.*, 2025).

7.3 Dynamics of Microalgae in Biological Soil Crusts (BSCs)

Biological Soil Crusts (BSCs) are complex microbial networks of algae, fungi, lichens, and bryophytes that act as essential ecosystem engineers in dryland environments (Gufwan *et al.*, 2025; Yang *et al.*, 2025). In arid zones where vascular plants are sparse, BSCs serve as a primary ground cover spanning 40% to 70% of the soil surface, where they aggregate loose soil particles to stabilise the soil profile, mitigate erosion, enhance water retention, and accelerate nutrient cycling and carbon storage (Rodríguez-Caballero *et al.*, 2018; Gufwan *et al.*, 2025). Regulated by soil moisture availability, these crusts range from under 1 mm in pioneer stages to 1-5 mm in mature cyanobacterial or green-algal matrices, gradually driving ecological succession towards moss- and lichen-dominated states as ecosystems transition from semiarid to humid conditions (Xiao *et al.*, 2016).

7.4 Microalgae-derived Biochar as a Structural Amendment

Converting microalgal biomass into biochar represents a sustainable strategy that locks photosynthetically sequestered carbon into a stable matrix for long-term storage (Fernández *et al.*, 2025). Due to an inherent richness in carbohydrates, proteins, lipids, and nucleic acids, microalgae yield high-quality biochar whose agricultural efficacy depends on its specific physical and chemical properties (Lee *et al.*, 2020). Synthesised via low-temperature, low-oxygen pyrolysis, this carbon-dense material exhibits high nutrient content and a robust ion-exchange capacity that improves long-term soil health while serving as an effective seed growth stimulant (Bi & He, 2022; Dziosa & Makowska, 2025). Furthermore, this stable structural amendment doubles as an efficient bioremediation tool, demonstrating high performance in adsorbing pollutants from both air and wastewater streams (Fernández *et al.*, 2025).

8. Bioremediation using Microalgae

Microalgae have gained significant research interest for the remediation of heavy metal pollution due to their ubiquity, cost-effectiveness, high pollutant-removal efficiency, and eco-friendly nature. Compared to higher plants, microalgae offer distinct physiological advantages, including accelerated growth rates and a simplified, non-toxic remediation pathway (Leong & Chang, 2020). Concurrently, microalgal systems are increasingly integrated into wastewater treatment processes. Beyond environmental remediation, microalgal cultivation yields high-value bioproducts including natural pigments and polyunsaturated fatty acids, while generating nutrient-dense biomass suitable for aquaculture feedstocks (Srimongkol *et al.*, 2022).

8.1 Bioremediation of Contaminated Soil

Microalgae effectively immobilise and accumulate heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) from contaminated soil matrices via coordinated bioaccumulation and biosorption mechanisms. The microalgal cell wall matrix is highly enriched with polysaccharides, proteins, and lipids, which present abundant functional groups (including carboxyl, hydroxyl, and amino groups) that chemically bind heavy metal ions and significantly minimise their bioavailability in the soil. Notably, *Chlorella vulgaris* and *Scenedesmus* sp. have demonstrated high extraction efficiencies for Cd and Pb from contaminated substrates (Leong & Chang, 2020).

Furthermore, microalgae degrade organic pollutants including synthetic pesticides, total petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs) through the secretion of extracellular enzymes and the generation of reactive oxygen species (ROS). This enzymatic degradation not only detoxifies the soil matrix but also stimulates indigenous soil microbial activity. For instance, the robust degradation of recalcitrant herbicides like atrazine has been documented in species such as *Chlorella pyrenoidosa* and *Scenedesmus obliquus* (Chakraborty *et al.*, 2025).

Ultimately, microalgae-mediated bioremediation represents an environmentally sustainable and economically viable strategy that minimises the necessity for synthetic chemical soil amendments. Unlike conventional physicochemical cleanups, this biological approach mitigates secondary pollution risks, preserves soil health, and generates valuable residual biomass for biofertiliser or bioenergy applications (Abdelfattah *et al.*, 2023; Lee *et al.*, 2020).

8.2 Agricultural Wastewater Treatment

The agricultural sector stands as both the primary consumer of global freshwater and the largest generator of wastewater discharges (Mateo-Sagasta *et al.*, 2013). Livestock production, in particular, generates substantial volumes of runoff heavily enriched with phosphorus and nitrogen, primarily in the form of phytotoxic ammonia. Beyond these primary macronutrients, agricultural effluents frequently contain residual pesticides, antibiotics, and other specialised animal pharmaceuticals. Runoff of unabsorbed manure nutrients into nearby aquatic ecosystems poses a significant risk of eutrophication, emphasising the critical need for advanced agricultural wastewater treatment technologies (Plöhn *et al.*, 2021).

Driven by rapid urbanisation, industrial expansion, and agricultural intensification, global wastewater volumes are systematically projected to increase by 24% by 2030 and 51% by 2050 (Qadir *et al.*, 2020). Microalgae-centric treatment systems offer a sustainable alternative to conventional engineering technologies, which are typically energy-intensive, yield excessive chemical sludge, and release significant greenhouse gases (Abdelfattah *et al.*, 2023).

Microalgae rapidly assimilate nitrogenous compounds (ammonia, nitrates) and orthophosphates from agricultural effluents, effectively lowering the overall nutrient load and chemical oxygen demand (COD). This remediation pathway prevents aquatic eutrophication while capturing and recycling discarded nutrients into functional biomass. Species such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Arthrospira platensis* have demonstrated exceptional nitrogen and phosphorus removal dynamics from livestock effluents and aquaculture wastewater (Ferro *et al.*, 2018; Zhang *et al.*, 2013).

8.3 Utilisation of Microalgae-treated Wastewater for Irrigation

Effluents treated via microalgal systems retain safe, highly bioavailable fractions of nitrogen, phosphorus, and essential trace minerals. When systematically reused for agricultural irrigation, this treated water enhances edaphic fertility and promotes crop productivity. Empirical studies indicate that crops irrigated with microalgae-mediated wastewater exhibit superior vegetative growth, higher yields, and improved post-harvest quality due to the additional supply of recycled nutrients (Xu *et al.*, 2019).

Utilising microalgae-treated wastewater for irrigation directly displaces the requirement for synthetic mineral fertilisers, fostering a highly sustainable, closed-loop circular nutrient economy. Additionally, the residual microalgal biomass harvested after the water treatment phase can be applied directly to the field as an organic soil amendment, providing organic matter and enhancing soil aggregate stability (Srimongkol *et al.*, 2022; Zhang *et al.*, 2013). This irrigation paradigm simultaneously conserves valuable freshwater reserves and minimises nutrient leaching into natural water bodies. The strategic integration of microalgal bioreactors into commercial farming operations offers a financially viable, multi-functional framework that achieves concurrent wastewater purification, biomass production, and nutrient-rich water recycling (Plöhn *et al.*, 2021; Ferro *et al.*, 2018).

9. Conclusion and Future Perspectives

Microalgae represent a pivotal, multi-functional cornerstone for the transition towards resilient, eco-efficient, and climate-smart food production systems. By restoring native soil structure, enhancing nutrient bioavailability, and deploying biodegradable biopesticides, these microorganisms effectively mitigate global reliance on hazardous synthetic agrochemicals. Beyond direct agronomic benefits, integrating microalgae into farming frameworks fulfils the mandates of a circular bioeconomy. Their dual capacity to recover essential nutrients from industrial wastewater streams and sequester atmospheric carbon dioxide converts ecological liabilities into high-value biomass and bioactive co-products.

However, translating this biological potential into widespread commercial viability requires overcoming critical bottlenecks. Current systemic constraints include prohibitive large-scale cultivation costs, unstable commercial formulations, and inconsistent performance across variable open-field environments. To bridge this gap, immediate research priorities must focus on advancing high-density cultivation technologies, refining downstream processing, and utilising genetic strain selection to optimise environmental resilience. Ultimately, addressing these technical hurdles will establish microalgae as an economically viable and ecologically indispensable pathway for global sustainable agriculture.

10. Limitation

This review synthesises evidence across diverse microalgal functions rather than evaluating a single crop, species, production system, or application method. The available evidence is distributed across biomass production, nutrient mobilisation, biostimulation, biopesticidal activity, soil amendment, and bioremediation, which limits direct comparison among studies. In addition, large-scale cultivation costs, formulation instability, and variable open-field performance constrain assessment of broad commercial applicability. Further comparative and field-based work is therefore needed to establish consistent performance across agricultural settings.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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