Buitenzorg
Journal of Tropical Science

Review Article

Microalgae-Based Fertilizers: Functions, Applications, and Market Prospects in Organic Farming

Datia Siti Nur Lisa[1], Aida Nursidah[2], Hani Susanti[3]*

[1] Department of Aquatic Products Technology, Faculty of Fisheries and Marine Sciences, IPB University, Bogor 16680, Indonesia
[2] Al Kautsar 561 Vocational School of Agropreneur, Tasikmalaya, Indonesia, 46198
[3] Research Center for Applied Microbiology, National Research and Innovation Agency (BRIN), Soekarno Science Center, Cibinong, Bogor 16911, Indonesia

*Corresponding author: hani.susanti@brin.go.id

ABSTRACT

Microalgae exhibit high biodiversity and are found in various habitats, including agricultural soil. The intensification of agriculture by chemical fertilizers results in significant environmental problems, including water pollution, accumulation of xenobiotic chemicals, diminished soil quality and fertility, and adverse effects on human health. Organic farming is highlighted as an effective approach to mitigate these problems. Microalgae offer key functions in agriculture as biostimulants, biofertilizers, biocontrol agents, sources of phytohormones, and soil moisturizers. These roles indicated the importance of microalgae in sustainable and organic agriculture, particularly for CO_2 sequestration, nutrient recycling from waste streams, and enhancing crop tolerance to abiotic stress. This review discusses practical application methods, field challenges, sustainable water sources for microalgae biomass production, market trends for biofertilizers made from this biomass, and long-term sustainability factors to establish safety and standardization protocols to ensure their reliability. Microalgae biomass can be produced in photobioreactors or open ponds and applied to agricultural land as wet inoculum, dry biomass, or extracted metabolites. Integration with irrigation and hydroponic systems offers additional potential for efficient nutrient delivery. The global market for microalgae fertilizer is projected to expand significantly due to increasing awareness of sustainable farming and rising demand for organic food. These fertilizers are eco-friendly, reduce nutrient waste and soil degradation, and are suitable for organic crop production as they are natural and free from synthetic chemicals or GMOs. In conclusion, microalgae represent sustainable and effective strategies to enhance soil fertility, stimulate plant growth, and strengthen crop protection in organic farming.

Keywords: biocontrol agents, algal biomass, circular bioeconomy, commercial viability, abiotic stress mitigation

Introduction

Microalgae, also known as microscopic algae, are single-celled organisms capable of oxygen production through photosynthesis. Microalgae have a high biodiversity, encompassing both prokaryotic and eukaryotic organisms. These organisms are classified into ten groups, primarily based on cell color, structure, organization, and life cycle. The groups are cyanophyte (cyanobacteria), glaucophyte, rhodophyte, chlorophyte, cryptophyte, haptophyte, dinophyte, heterocontophyte, chloroarachnide, and euglenid (Blaby-Haas & Merchant, 2019; De Clerck et al., 2012).

Microalgae inhabit various environments, particularly freshwater and marine systems, and play an important role as primary producers in aquatic ecosystems. Moreover, microalgae can be observed in associated to plant tissues and within soil (Lee & Ryu, 2021). Therefore, these microbes exist and play a role in agricultural land.

Intensification of agriculture is implemented in land-processing activities as an attempt to improve food sustainability. Chemical fertilizers have historically been a massive strategic effort to increase agricultural output, but their long-term use poses significant challenges to sustainability. Spesifically, these practices result in serious side effects on environmental conditions, including the degradation of clean water resources, the accumulation of xenobiotic compounds and the decline in soil quality and fertility (Gaikwad et al., 2023; Gonçalves, 2021). The intensification of agriculture also negatively affects human health (Lam et al., 2018). Therefore, organic farming is considered the most effective approach to reduce the impact of conventional farming, with its best practice advantages illustrated in Figure 1. Microalgae have been suggested to support the implementation of organic farming by involving them in agricultural land.

Numerous species of microalgae play a role in enhancing the quality and productivity of agricultural land, primarily due to their highly varied and rich biochemical composition. Microalgae are exceptionally well-suited for deployment as potent biofertilizers and biostimulants. Formally, a biostimulant is classified as any substance or microorganism applied to the plant or its root zone (rhizosphere) that enhances natural processes, thereby improving nutrient uptake, nutrient use efficiency (NUE), tolerance to abiotic stress, or crop quality, independent of the concentration of nutrients it may contain (Parmar et al., 2023).

The ability of microalgal biomass to positively impact soil health and plant growth is attributed to a wide variety of biomolecules, including soluble amino acids (AA), biomineral conjugates, polysaccharides, and phytohormones. These metabolites are reported to improve soil fertility, provide resistance to abiotic stress, stimulate defense responses against pathogens and infections, and optimize the absorption of soil nutrients such as nitrogen (N), potassium (K), phosphorus (P), and essential minerals (Parmar et al., 2023).

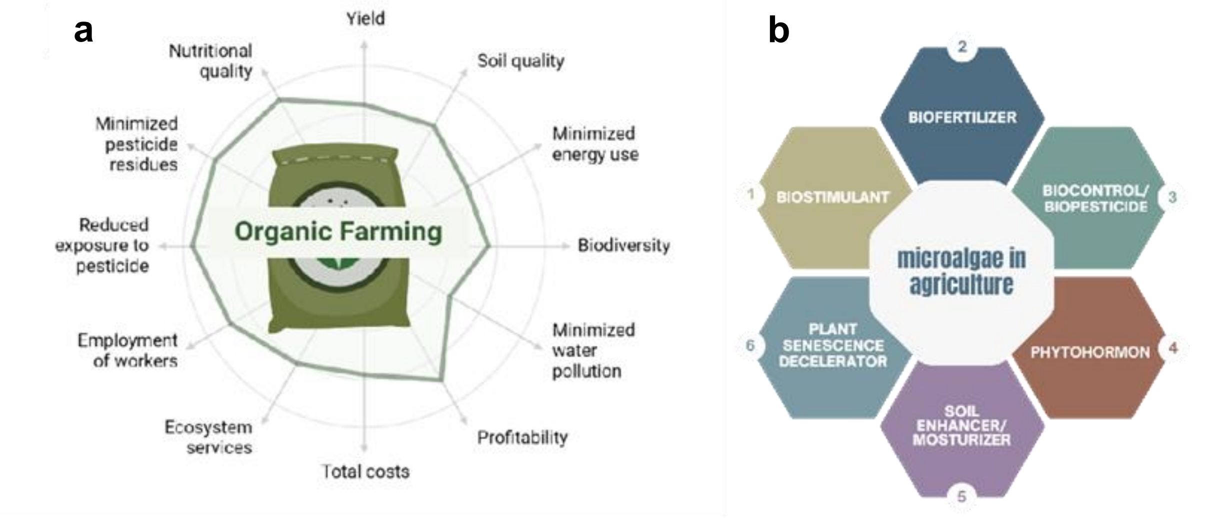

Fig. 1. Schematic advantages of organic farming (a) and schematic functional role of microalgae in agriculture (b).

Previous studies have shown that the active components of exopolysaccharides (EPS) produced by microalgae can improve soil structure and reduce salt concentrations in highly saline soils around plant roots (Xu et al., 2023). Furthermore, microalgal EPS can also form biocrusts in sandy soils and rehabilitate degraded drylands (Chamizo et al., 2020). Other components, such as phytohormones like auxin (IAA) and gibberellin (GA), are synthesized by microalgae and are directly related to root growth, seed germination initiation, and stem elongation (Kapoore et al., 2021). As phototrophic organisms with high photosynthetic efficiency, microalgae utilize sunlight and carbon dioxide (CO_2) as carbon sources, thereby contributing to CO_2 sequestration and climate change mitigation (Parmar et al., 2023).

The groups of microalgae that are commonly found in both organic and non-organic farming are cyanophyte, chlorophyte, heterocontophyte and euglenid. *Arthrospira* (*spirulina*), *Dunaliella*, *Nostoc*, *Scenedesmus*, and *Chlorella* are microalgae genera have been used for agriculture (Figure 2). Previous study reported that as many as 37 genera have been found from soil and water samples in the organic basin of Subak, Jatiluwih, Tabanan (Fitriyani et al., 2019). The diversity and abundance of such microalgae is influenced by the crop type, the ability of microalgae to adapt to changing environmental conditions (seasons, sunlight intensity, etc.), and the content of organic compounds in the soil. The occurrence of xenobiotic substances in soil, such as chemical pesticides, also has a detrimental effect on the variety of microalgae. *Vice versa*, microalgae can be introduced and incorporated into agricultural soil as a biofertilizer or organic fertilizer to reduce reliance on synthetic chemical fertilizers, provide essential nutrients, and improve soil quality.

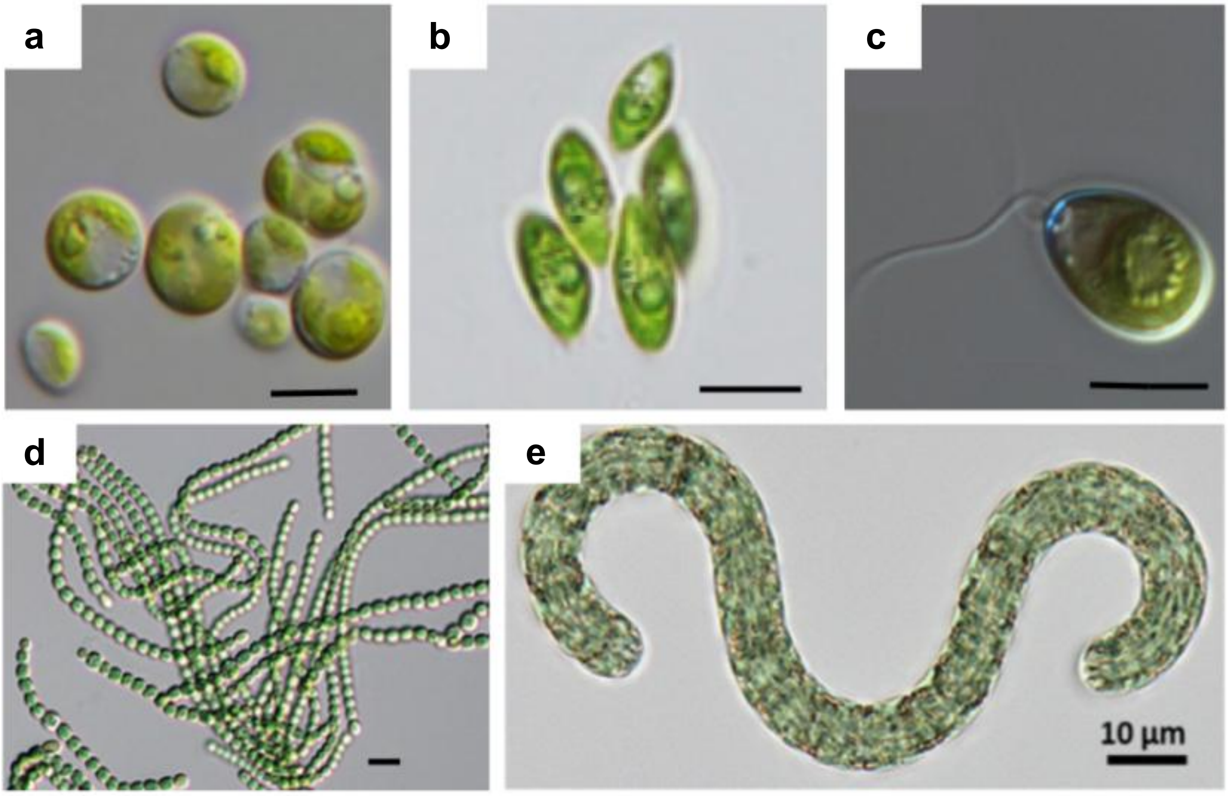

Fig. 2. Morphology of species used for agriculture. (a) *Chlorella* sp. (Darienko et al., 2019). (b) *Scenedesmus* sp. (Mercado et al., 2020). (c) *Dunaliella* sp. (Preetha et al., 2012). (d) *Nostoc* sp. (Hong et al., 2018). (e) *Arthrospira* sp. (Jung et al., 2021). Scale bars = 10 µm.

Microalgae Utilization in Organic Farming Land

Microalgae perform at least six functions in agricultural systems (Figure 1), particularly within the context of organic farming:

Microalgae as a biostimulant in organic farming

Biostimulants are organic chemicals derived from natural materials that can be sprayed in small quantities to enhance plant growth and development, regardless of whether the environmental conditions are ideal or if the plants have been damaged. Biostimulant compounds derived from microalgae include polysaccharides, phenolic compounds, vitamins, and other sources (Abo-Shady et al., 2023; Gonçalves, 2021).

Microalgae as a biofertilizer (biological fertilizer

Biological fertilizer is a substance that comprises microorganisms or natural elements that can enhance the biological and chemical properties of soil, promote plant growth, and replenish soil fertility. Microalgae enhance soil nutrient levels, particularly nitrogen and phosphorus, which are crucial for optimal crop development and yield improvement. Furthermore, the presence of microalgae in soil can increase the availability of nutrients in the soil through nitrogen fixation processes, CO_2 fixation, inorganic phosphorus formation, and mineralization (Gonçalves et al., 2023; Lam et al., 2018).

Microalgae biomass is a naturally occurring substance that contains a high concentration of organic compounds derived from the process of converting CO_2 into biomass. As a result, these microorganisms can serve as a valuable source of both macro- (carbon, nitrogen, phosphorus) and micro- (potassium, magnesium, sulphur, and iron) nutrients, including vitamins B1, B2, B3, and B12 (Ronga et al., 2019). Microalgae-derived organic fertilizers have been utilized on a range of crops, such as tomatoes, turnips, salads, spinach, cabbage, and cucumbers (Lee & Ryu, 2021).

Microalgae as a biocontrol or biopesticide

Microalgae as a biocontrol or biopesticide, exhibiting properties such as antimicrobial, antioxidant, antiviral, antifungal, anti-nematode, and pest chemicals (Lee & Ryu, 2021). Microalgae can exert control over diseases and pests through many processes, including growth inhibition, activation of plant immune responses, production of enzymes that degrade pathogen or pest cell walls, and repellent activity.

In addition, microalgae-derived biopesticides encompass cyanotoxin chemicals synthesized by the cyanophyta group. Currently, the bio-controlled activity of microalgae is undergoing *in vivo* testing, but additional field trials are needed. Utilizing microalgae-based organic fertilizer in agricultural fields can diminish reliance on chemical pesticides, hence enhancing the feasibility of future organic farming practices (Gurau et al., 2025; Parmar et al., 2023; Tiwari, 2016).

Microalgae as a valuable source of phytohormones

Phytohormones are signaling molecules that regulate various processes in plant cells, including growth and defense against pathogens. Certain microalgae belonging to the cyanophytes, chlorophytes, rhodophytes, and heterokontophytes groups have the ability to synthesize significant phytohormones including oxygen, abscisic acid, cytokinin, ethylene, and gibberellins (Gonçalves, 2021; Romanenko et al., 2016).

Microalgae enhance soil conditions

Microalgae enhance soil conditions by moisturizing the soil through the synthesis of mucous exopolysaccharides. This process also helps increase the pH of acidic soil, regulate salinity, and decrease heavy metal concentrations. Furthermore, microalgae establish symbiotic relationships with bacteria, fungi, and archaea to produce biocrust, which enhances soil structure and stability. Microalgae enhance their resistance to harmful environmental factors by producing extracellular polymeric substances (EPS) and antioxidant chemicals, including carotenoids, polysaccharides, terpenoids, and phenolic compounds (Gonçalves, 2021; Paul et al., 2024; Ronga et al., 2019).

Microalgae decelerating plant senescence

This capability has been confirmed through rigorous testing and practical implementations. *Chlorella vulgaris* has the ability to extend the lifespan of strawberries, beets, and salad plants. Concurrently, the utilization of *C. fusca* can decelerate the process of aging on the stems and blossoms of *Erinus alpinus* plants (Lee & Ryu, 2021). The detailed mechanisms by which microalgae can slow plant aging remain undisclosed (Ronga et al., 2019).

Therefore, microalgae can be introduced and incorporated into agricultural soil as biofertilizers or organic fertilizers to reduce the dependency on synthetic chemical inputs and mitigate the presence of xenobiotic compounds. This strategic necessity aims to identify sustainable, biologically safe alternatives to intensive farming, which forms the core research rationale of this review, given that the full potential of microalgae is currently hampered by significant commercial and scientific barriers that must be systematically overcome.

Physiology of Microalgae as Fertilizer

Microalgae rely on carbon-concentrating mechanisms (CCMs) to optimize photosynthesis when external CO_2 levels are limiting (Giordano et al., 2005; Kupriyanova et al., 2023). These systems actively accumulate inorganic carbon (CO_2 and HCO_3^-) around RuBisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase), the enzyme responsible for fixing CO_2 into organic carbon. In depleted soil environments with low CO_2 concentrations, microalgae upregulate bicarbonate transporters, CO_2-converting enzymes like carbonic anhydrases (CAs) concentrate CO_2 near RuBisCO inside microcompartments such as pyrenoids in eukaryotic algae, and carboxysomes in cyanobacteria. Some cyanobacteria combine CCM with heterocyst-based N_2 fixation, enriching soil with both carbon and nitrogen. However, in a CO_2-enriched environment, microalgae downregulate CCM genes and transporters to save energy. Moreover, photosynthesis proceeds passively due to high CO_2 diffusion. Microalgae grown under both low and high CO_2 accumulate large amounts of biomass rich in organic carbon (proteins, carbohydrates, and lipids). When applied to soils, this biomass enhances organic matter content. This efficiency in carbon capture and assimilation of CCM is what enables microalgae to produce organic matter, oxygen, and bioactive compounds that, when applied to soils, enhance fertility and crop productivity. CCM-driven photosynthesis produces exudates (organic acids, polysaccharides) that can solubilize phosphate, chelate micronutrients, and stimulate microbial activity in soils.

Microalgae, including cyanobacteria, have evolved specialized mechanisms to acquire phosphorus (P) from environments where it is scarce. Since most soil phosphorus exists in insoluble or organic forms, microalgal activity helps convert these into plant-available orthophosphate (PO_4^{3-}). When microalgae are applied as biofertilizers, their ability to mobilize P enhances soil fertility and reduces reliance on synthetic P fertilizers. Phosphorus uptake in microalgae occurs through various mechanisms, such as direct uptake of orthophosphate (PO_4^{3-}), enzymatic solubilization of organic phosphorus by phosphatases, release of organic acids (gluconic, oxalic, and citric acids) that lower soil pH. Additionally, microalgae of performing symbiotic interactions with phosphate-solubilizing bacteria in the rhizosphere, thereby enabling plants plants to obtain bioavailable of phosphorus (Abo-Shady et al., 2023; Solomon et al., 2023).

Microalgae also have the potential to be used as fertilizer because they can stimulate the uptake of nitrogen and the activity of nitrate reductase, while also providing important macro- and micro-nutrients. Some microalgal components, like phytohormones, can stimulate the production of antifungal substances, and crude polysaccharides from microalgae can have a biostimulant effect on plants.

Provision of Microalgae for Application in Organic Soil

Microalgae biomass production can be carried out with several strategies including using photobioreactors or open ponds (Ronga et al., 2019). Optimal growth conditions for microalgae are achieved in photobioreactor systems. On the other hand, using open ponds is more feasible, but they need to be well-managed to avoid losing productivity because of predation, contamination, and competition with other microorganisms that live in the pond. Biomass production processes can either use commercial media or use organic waste in the context of biorefinery. Organic waste after undergoing pretreatment can be used as a source of nutrients for microalgae growth.

Biomass obtained directly from algal blooms could serve as a potential source of microalgae biomass for organic farming. Consequently, the issue of algae blooming is no longer regarded as a severe environmental and societal problem. Nevertheless, it is essential to ensure that biomass from algal blooms does not contain any harmful compounds.

Microalgae biomass harvesting is carried out by various techniques, such as filtration, flocculation, centrifugation, and biomass sedimentation. The biomass of microalgae utilized in organic farming can be introduced onto agricultural land either as wet biomass by directly inoculating microalgae seedlings, or as dry biomass. In addition, it can also use materials contained in biomass as primary metabolites (polysaccharides, lipids, and proteins), secondary metabolites (pigments, carotenoids, phenolic compounds, terpenoids, etc.), vitamins, and minerals.

The biomass extraction method is conducted to isolate the metabolite component from the microalgae cells (Ronga et al., 2019). Subsequently, the extract is applied to the crop via spraying. Microalgae have the ability to release certain nutrients into liquid media. After undergoing filtration, these compounds can also be utilized to provide advantages for the field of agriculture.

Another approach involves utilizing a microalgae consortium, predominantly composed of cyanophyta, to augment the function of microalgae in plants and soil (Jose et al., 2024; Lam et al., 2018). Integrating microalgae growing with hydroponic systems or incorporating microalgae into agricultural irrigation systems is a promising approach to enhance the utilization of microalgae in organic farming.

Biofertilizer Application Based on Microalgae, Soil, and Plant Interaction

Microalgae, soil, and plants (MSP) are interrelated components of an ecosystem that establish both beneficial and detrimental interactions. Microalgae serve as constituents of the microbiome, suppliers of organic nutrients, biofixation agents, and soil aggregators, while soil functions as a habitat and medium facilitating the ongoing interaction between microalgae and plants. Plants utilize soil as a growth substrate and as a medium for nutrient transfer from the environment to the root system. Microalgae affect soil conditions, agricultural crops and pathogens in agricultural land. In the last 10 years, researchers around the world, especially in the Asian region, have studied the potential of microalgae in agriculture. The scientific report reveals a good and beneficial interaction between microalgae,

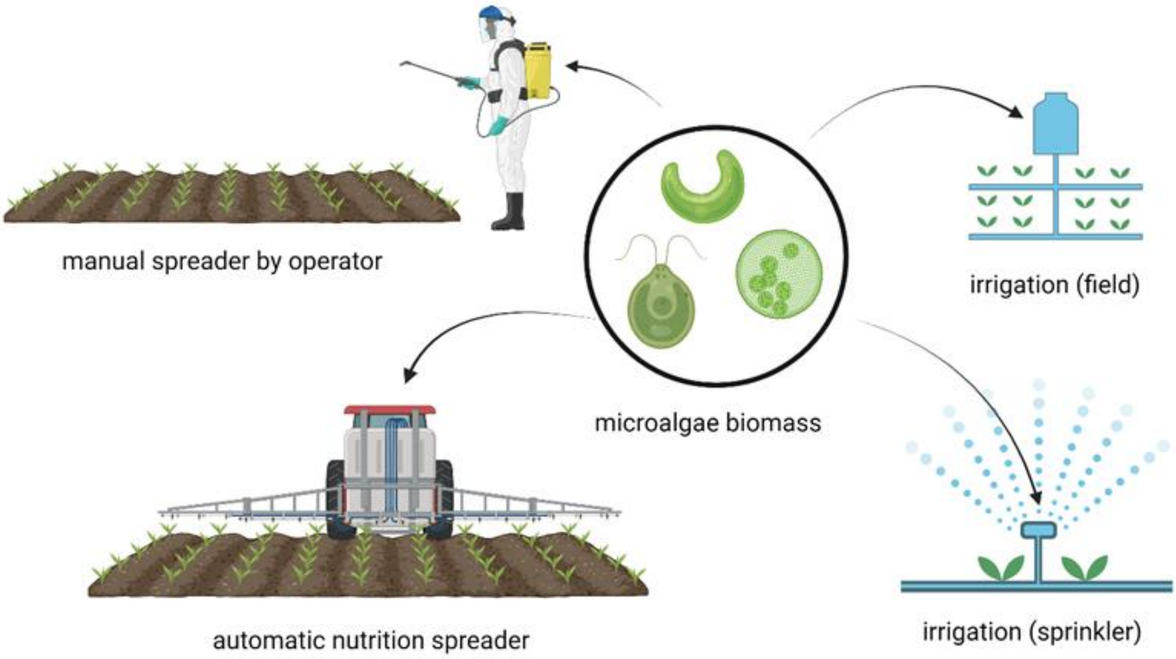

Fig. 3. Application of microalgae in organic farming land.

plants and soil (Gonçalves et al., 2023; Mutum et al., 2022).

Microalgae can enhance the productivity of organic farming land by comprehending the favorable synergistic relationships among microalgae, plants, and soil. Additional field trials are necessary for the implementation of organic farming (Figure 3), specifically in relation to the production of microalgae biomass.

Application Challenges in the Field

Microalgae application in agricultural land has been carried out in several countries including India (Tiwari, 2016), Russia (Abdulagatov et al., 2018), Nigeria (Adesalu & Olugbemi, 2015), and South Korea (Lee & Ryu, 2021). The utilization of microalgae in organic farming is currently limited. The application of microalgae from the cyanophyta group as an organic fertilizer has been conducted in India (Jurado-Flores et al., 2025; Priya et al., 2022; Ramakrishnan et al., 2023). Cyanophyta (blue-green algae) have been utilized as organic fertilizer in uncultivated land in Indonesia (Eginarta et al., 2021). However, its application in other agricultural land remains unknown.

Further research and improvement are necessary to obtain a comprehensive understanding of the roles among microalgae, plants, and soil in order to determine the most effective utilization of microalgae in agriculture. Furthermore, it is imperative to create and disseminate cost-effective microalgae cultivation methods to the society, particularly to practitioners of organic farming. The main challenge is the availability of sufficient biomass of microalgae at cheap production costs for use on large farmland (Gaikwad et al., 2023; Gonçalves, 2021). For that, the biorefinery's strategy toward microalgae waste is expected to reduce production costs. In addition, combined cultivation of microalgae and plants with hydroponic systems can be an alternative to obtaining biomass while using it as a biostimulant, biofertilizer, etc.

Selecting microalgae strains based on soil characteristics and plant types will affect the success of applications in the field. Indigenous microalgae found directly in organic soil and easily cultivated can be the primary candidate for application. The presence of biotic and abiotic elements in the surrounding environment might impact the growth of microalgae on agricultural land. For instance, the presence of other organisms that feed on microalgae can decrease the abundance of microalgae on farmland.

Water Source of Microalgae-based Fertilizer

Fresh water and seawater are the two main sources of microalgae biomass production for fertilizer. Since there is a more significant trend in farming more sustainable food products, this is an opportunity for the microalgae fertilizer market. There is also an increase in demand for microalgae made from seawater rather than freshwater, so as demand increases, people tend to move from microalgae in freshwater to seafood. Wastewater also represents a practical source of water for producing microalgae biomass. By using its nutrient content, cultivation costs can be reduced while helping to lessen negative impacts on the local ecosystem. Pre-treatment is essential in cases when the wastewater contains substances that are detrimental to the growth of microalgae and hinder their ability to produce biomass.

Microalgae in Fertilizer Market

According to Future Market Insights (FMI) analysis, demand for microalgae in the fertilizer sector is expected to experience stable growth. The FMI is an organization located in Delaware, USA, which continuously performs market research. The organization examines the factors driving market demand and points out opportunities that could support growth across sources, applications, sales channels, and end-use sectors over the coming decade. The FMI estimates indicate that demand for microalgae in the fertilizer sector is expected to exceed US$28.7 million by 2033, up from US$11 million in 2023. During the assessment period from 2023 to 2033, demand for microalgae in fertilizer sectors is projected to increase by 10% Compound Annual Growth Rate (CAGR). This is due to an increased level of concern regarding the awareness in choosing sustainable farming. It aims to minimize the environmental impact of conventional farming practices. In addition, demand for food and organic products is growing globally. Microalgae-based fertilizer aligns

Table 1. Countries produce microalgae-based biofertilizers.

Country Name	Company Name	Product Name	References (website)
United States	Algenol Biotech	Algenol	https://www.algenol.com
	TrueAlgae	TrueSolum	https://www.truesolum.com
	Heliae Development, LLC	Phycoterra	https://phycoterra.com
	Kemin Crop Technology	Valena™	https://www.kemin.com
Spain with subsidiary based in the United States	AlgaEnergy S.A. Inc	AlgaEnergy	https://ag.algaenergy.com
France	NeoEarth	NeoEarth Fertilizer	https://www.neoearth.fr
Japan	Euglena Co., Ltd. Collaboration with Kobashi Kogyo Co., Ltd.	Japanese name (Midorimushi) hereinafter Euglena soil	https://www.euglena.jp
Indonesia	PT Algae Park Indonesia Mandiri	Algalizer	https://algaepark.co.id

with organic farming practices since it is derived from natural sources. This plant does not contain synthetic chemicals or organisms that have undergone genetic modification (GMOs). Therefore, microalgae-based fertilizer is suitable for organic crop production.

Microalgae-based fertilizer has been used in North America, Europe, Asia Pacific, Latin America, the Middle East, and Africa. Some of the companies that sell microalgae-based fertilizers are represented as global stakeholders in advancing the commercialization of microalgae-derived biofertilizers, demonstrating the market's maturity in developed regions (Table 1).

However in Asia, especially Indonesia, commercialization is still limited, with only one company actively engaged in the production of microalgae-based biofertilizer despite the country's rich microalgal biodiversity and high agricultural demand. The market for microalgae fertilizers is experiencing remarkable growth as an innovative and sustainable solution to agricultural and horticultural practices. Microalgae-based plants, derived from microorganisms such as *Chlorella* and *Arthrospira*, are rich in vital nutrients such as nitrogen, phosphorus, potassium, and various micronutrients. These natural fertilizers not only provide plants with essential nutrients but also offer additional benefits such as improved soil health, improved harvest yields, and improved resistance to environmental stress.

One of the main advantages of microalgae fertilizers is their eco-friendly nature. They have a lower environmental impact compared to traditional chemical fertilisers, as they reduce the risk of nutrient waste, groundwater contamination, and soil degradation. In addition, microalgae-based fertilizers are ideal for organic and sustainable farming practices, in line with the growing demand for environmentally responsible farming.

There is currently a growing focus on conducting more research and development activities in order to enhance the composition and utilization of microalgae fertilizer in the market. With the aim of finding substitutes for conventional fertilizers that may harm ecosystems, both farmers and agriculturalists are actively seeking alternatives. Consequently, the microalgae market is expected to keep going up. This trend fits with a larger move toward more sustainable and regenerative farming methods, which makes microalgae fertilizer a promising part of the future of farming. The market for new fertilizers made from microalgae is affected by changes in the market. This dynamic includes a number of factors, such as new technologies, changing consumer tastes, government rules, environmental issues, and the state of the global economy.

The rapid growth of the population has led to an increase in the demand for food production, while putting pressure on agricultural land resources. Scientists have concentrated their efforts on microalgae as a sustainable and feasible substitute for nourishing plants in order to tackle this challenge.

Factors Affecting the Sustainability of Microalgae in the Market

Several variables affect the sustainability of microalgae in the market (Figure 4). Research collaboration among fertilizer manufacturers with research institutes or experts in microalgae culture is important to collectively create novel formulations for fertilizers that are based on microalgae. Such collaboration could lead to the development of more efficient and nutritionally dense products.

Producers of microalgae fertilizer might establish distribution agreements with agricultural suppliers to enhance the accessibility of their products to farmers. These collaborations might facilitate the expansion of the customer reach. Furthermore, strategic alliances can be established between fertilizer producers and organizations specializing in soil health and agricultural solutions. This collaboration aims to provide farmers with a comprehensive bundle of services and products. One possible approach is to integrate microalgae fertilizer with soil conditioner and precision farming technology. Companies that own unique technology for growing and processing microalgae can give licenses to fertilizer makers. This lets them make microalgae-based products more efficiently and cheaply.

Fig. 4. Factors affecting the sustainability of microalgae in the market.

Major agricultural corporations are contemplating the purchase of microalgae cultivation facilities or start-ups in order to incorporate them into their supply chains. This vertical integration strategy can afford them greater authority in managing the production and ensuring the quality of fertilizers derived from microalgae.

Large multinational agricultural corporations have the opportunity to purchase smaller local producers of microalgae fertilizers in order to extend their market reach into other regions or nations. These market expansion strategies can enable them to capitalize on emerging markets and broaden their range of product offerings.

The variety of microalgae-based fertilizers, including biofertilizers, biostimulants, biofungicides, slow-release nutrient carriers, and soil conditioners, can have a big impact on how long microalgae stay on the market. Instead of just one type of fertilizer, companies can meet a wide range of agricultural needs, such as improving NPK levels, soil health, pest resistance, biofertilizers made from algae growing in wastewater, or biostimulants made from protein-rich strains. Microalgae companies can use fertilizers that contain microalgae extracts and biochar-based soil additions in organic farming. A variety of fertilizer products can be offered to reach more customers and keep demand steady.

Interesting Facts about the Microalgae Fertilizer Industry

Microalgae are highly efficient in nutritional recovery and have a strong potential as a source of fertilizer. However, large-scale commercial production of microalgae fertilizers still has many challenges. Microalgae-based fertilizer plants are currently under development and require additional comprehensive research in both the United States (US) and the United Kingdom (UK), as these countries are at the forefront of research and development in this field.

Rising demand for organic food will lead to a corresponding increase in organic output, necessitating a bigger quantity of organic fertilizer. The scarcity of biodiesel will result in a rise in the fertilization of microalgae. Microalgae also enables research and development to assess the effectiveness of businesses in providing organic fertilizer for production. This tendency also promotes a transition towards improved agricultural techniques to enhance soil stability and boost yield. Funding is available for the procurement of raw materials, agrochemicals, and other necessary products to enhance the demand for microalgae fertilizer. Consumers currently enjoy enhanced lifestyles and adopt healthier habits. This phenomenon has resulted in the development of superior and more natural food products, hence increasing the need for organic fertilizer to enhance the quality of food. The industry can derive long-term advantages from this reality, as health is intricately connected to the quality of life.

Arthrospira, *Chlorella*, *Dunaliella*, *Schizochytrium*, *Euglena*, *Nannochloropsis*, *Nostoc*, and others are some of the major species used in microalgae fertilizers. *Arthrospira* is the leading species that is used in biofertilizers. Nevertheless, maintaining the product quality of microalgae-based fertilizer raises multiple concerns.

Conclusion

Microalgae offer a sustainable and effective solution for enhancing soil fertility, plant growth, and crop protection within organic farming systems. Their diverse functional roles and eco-friendly nature position them as a promising alternative to conventional agricultural inputs, with a growing market demand driven by the shift towards sustainable practices. Further research and cost-effective production methods are crucial for wider adoption and the maximization of their agricultural benefits.

Acknowledgements

Part of illustrations are created with BioRender.com and canva.com.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Abdulagatov, I. M., Alkhasov, A. B., Dogeev, G. D., Tumalayef, N. R., Aliyev, R. M., Badavov, G. D., & Aslan, M.A. (2018). Microalgae as a Renewable Raw Material for Agriculture, Biofuel Production and Purification of Geothermal Water from Phenols. *PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering* Stanford University, Stanford, California, February 12-14.

Abo-Shady, A. M., Osman, M. E. A. H., Gaafar, R. M., Ismail, G. A., & El-Nagar, M. M. F. (2023). Cyanobacteria as a valuable natural resource for improved agriculture, environment, and plant protection. *Water, Air, and Soil Pollution*, *234*(313), 1–21. https://doi.org/10.1007/s11270-023-06331-7

Adesalu, T. A., & Olugbemi, O. M. (2015). Soil algae: a case study of two vegetable farmlands in Lagos and Ogun States, Southwest Nigeria. *Ife Journal of Science*, *17*(3), 765–772.

Blaby-Haas, C. E., & Merchant, S. S. (2019). Comparative and functional algal genomics. *Annual Review of Plant Biology*, *70*, 605–638. https://doi.org/https://doi.org/10.1146/annurev-arplant-050718-095841

Chamizo, S., Mugnai, G., Rossi, F., Certini, G., & Phillipis, R. D. (2018). Cyanobacteria inoculation improves soil stability and fertility on different textured soils: gaining insights for applicability in soil restoration. *Frontiers in Environmental Science*, 6. https://doi.org/10.3389/fenvs.2018.00049

Darienko, T., Rad-Menéndez, C., Campbell, C., & Pröschold, T. (2019). Are there any true marine *Chlorella* species? Molecular phylogenetic assessment and ecology of marine *Chlorella*-like organisms, including a description of *Droopiella* gen. nov. *Systematics and Biodiversity*, *17*(8), 811–829. https://doi.org/10.1080/14772000.2019.1690597

De Clerck, O., Bogaert, K. A., & Leliaert, F. (2012). Chapter two - Diversity and evolution of algae: primary endosymbiosis. *Advances in Botanical Research*, *64*, 55–86. https://doi.org/10.1016/B978-0-12-391499-6.00002-5

Eginarta, W. S., Nuraini, Y., & Purwani, J. (2021). Effectivity of various carriers of cyanobacteria biofertilizer on growth and yield of upland rice Situ

Bagendit variety. *Jurnal Tanah dan Sumberdaya Lahan*, *8*(2), 415–426. https://doi.org/10.21776/ub.jtsl.2021.008.2.13

Fitriyani, S., Atmaja, I. W. D., & Soniari, N. N. (2019). Genus alga pada lahan sawah organik yang ditanami padi lokal dan inhibrida di Subak Jatiluwih, Tabanan. *Agrotrop: Journal on Agriculture Science*, *9*(2), 112–124.

Gaikwad, A. S., Margal, P. B., & Titirmare, N. S. (2023). Soil degradation and remediation: strategies for restoring soil quality. *Advances in Soil Science*, *1*(9), 349–390. https://doi.org/10.5281/zenodo.8330919

Giordano, M., Beardall, J., & Raven, J. A. (2005). CO_2 concentrating mechanisms in algae: mechanisms, environmental modulation, and evolution. *Annual Review of Plant Biology*, *56*, 99–131. https://doi.org/10.1146/annurev.arplant.56.032604.144052

Gonçalves, A. L. (2021). The use of microalgae and cyanobacteria in the improvement of agricultural practices: a review on their biofertilizing, biostimulating and biopesticide roles. *Applied Sciences (Switzerland)*, *11*, 1–21. https://doi.org/10.3390/app11020871

Gonçalves, J., Freitas, J., Fernandes, I., & Silva, P. (2023). Microalgae as biofertilizers: a sustainable way to improve soil fertility and plant growth. *Sustainability*, *15*(16), 12413. https://doi.org/10.3390/su151612413

Gurau, S., Imran, M., & Ray, R. L. (2025). Algae: a cutting-edge solution for enhancing soil health and accelerating carbon sequestration–a review. *Environmental Technology and Innovation*, *37*, 1–13. https://doi.org/10.1016/j.eti.2024.103980

Hong, J. W., Kim, O. H., Jo, S. W., Kim, H., Jeong, M. R., & Yoon, H. S. (2018). Characterization of alkane-producing *Nostoc* sp. isolated from a summer bloom for biofuel potential. *Journal of Biobased Materials and Bioenergy*, *12*(3), 244–251. https://doi.org/10.1166/jbmb.2018.1757

Jose, S., Malla, M. A., Renuka, N., Bux, F., & Kumari, S. (2024). Cyanobacteria-green microalgae consortia enhance soil fertility and plant growth by shaping the native soil microbiome of *Capsicum annuum*. *Rhizosphere*, *30*, 100892. https://doi.org/10.1016/j.rhisph.2024.100892

Jung, C. H. G., Braune, S., Waldeck, P., Küpper, J. H., Petrick, I., & Jung, F. (2021). Morphology and growth of *Arthrospira platensis* during cultivation in a flat-type bioreactor. *Life*, *11*(6), 536. https://doi.org/10.3390/life11060536

Jurado-Flores, A., Heredia-Martínez, L. G., Torres-Cortes, G., & Díaz-Santos, E. (2025). Harnessing microalgae and cyanobacteria for sustainable agriculture: mechanistic insights and applications as biostimulants, biofertilizers and biocontrol agents. *Agriculture*, *15*(17), 1842. https://doi.org/10.3390/agriculture15171842

Kapoore, R. V., Wood, E. E., & Llewellyn, C. S. (2021). Algae biostimulants: a critical look at microalgae biostimulants for sustainable agriculture practices. *Biotechnology Advances*, *49*, 107754. https://doi.org/10.1016/j.biotechadv.2021.107754

Kupriyanova, E. V., Pronina, N. A., & Los, D. A. (2023). Adapting from low to high: an update to CO_2-concentrating mechanisms of cyanobacteria and microalgae. *Plants*, *12*(7), 1569. https://doi.org/10.3390/plants12071569

Lam, S., Pham, G., & Nguyen-Viet, H. (2018). Emerging health risks from agricultural intensification in Southeast Asia: a systematic review. *International Journal of Occupational and Environmental Health*, *23*(3), 250–260. https://doi.org/10.1080/10773525.2018.1450923

Lee, S. M., & Ryu, C. M. (2021). Algae as new kids in the beneficial plant microbiome. *Frontiers in Plant Science*, *12*, 599742. https://doi.org/10.3389/fpls.2021.599742

Mercado, I., Álvarez, X., Verduga, M. E., & Cruz, A. (2020). Enhancement of biomass and lipid productivities of *Scenedesmus* sp. cultivated in the wastewater of the dairy industry. *Processes*, *8*(11), 1–19. https://doi.org/10.3390/pr8111458

Mutum, L., Janda, T., Ördög, V., & Molnár, Z. (2022). Biologia futura: potential of different forms of microalgae for soil improvement. *Biologia Futura*, *73*, 1–8. https://doi.org/10.1007/s42977-021-00103-2

Parmar, P., Kumar, R., Neha, Y., & Srivatsan, V. (2023). Microalgae as next generation plant growth additives: functions, applications, challenges and circular bioeconomy based solutions. *Frontiers in Plant Science*, *14*, 1073546. https://doi.org/10.3389/fpls.2023.1073546

Paul, S., Parvez, S. S., Goswami, A., & Banik, A. (2024). Exopolysaccharides from agriculturally important microorganisms: conferring soil nutrient status and plant health. *International Journal of Biological Macromolecules*, *262*(2), 1073546. https://doi.org/10.1016/j.ijbiomac.2024.129954

Preetha, K., John, L., Subin, C. S., & Vijayan, K. K. (2012). Phenotypic and genetic characterization of *Dunaliella* (Chlorophyta) from Indian salinas and their diversity. *Aquatic Biosystems*, *8*(1), 27. https://doi.org/10.1186/2046-9063-8-27

Priya, H., Dhar, D. W., Singh, R., Kumar, S., Dhandapani, R., Pandey, R., Govindasamy, V., & Kumar, A. (2022). Co-cultivation approach to decipher the influence of nitrogen-fixing cyanobacterium on growth and N uptake in rice crop. *Current Microbiology*, *79*, 53. https://doi.org/10.1007/s00284-021-02732-1

Ramakrishnan, B., Maddela, N. R., Venkateswarlu, K., & Megharaj, M. (2023). Potential of microalgae and cyanobacteria to improve soil health and agricultural productivity: a critical view. *Environmental Science: Advances*, *2*, 586–611. https://doi.org/10.1039/d2va00158f

Romanenko, K. O., Kosakovskaya, I. V., & Romanenko, P. O. (2016). Phytohormones of microalgae: biological role and involvement in the regulation of physiological processes. *International Journal on Algae*, *18*(2), 179–201. https://doi.org/10.1615/InterJAlgae.v18.i2.70

Ronga, D., Biazzi, E., Parati, K., Carminati, D., Carminati, E., & Tava, A. (2019). Microalgal biostimulants and biofertilisers in crop productions. *Agronomy*, *9*(4), 192.

https://doi.org/10.3390/agronomy9040192

Solomon, W., Mutum, L., Janda, T., & Molnár, Z. (2023). Potential benefit of microalgae and their interaction with bacteria to sustainable crop production. *Plant Growth Regulation*, *101*(1), 53–65. https://doi.org/10.1007/s10725-023-01019-8

Tiwari, A. (2016). Organic fertilizer from microalgae and its application in agriculture. *Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, *10*(2), 73–76.

Xu, Q., Zhu, T., Zhao, R., Zhao, Y., Duan, Y., Liu, X., Luan, G., Hu, R., Tang, S., Ma, X., Liu, Y., Li, S., & Lu, X. (2023). *Arthrospira* promotes plant growth and soil properties under high salinity environments. *Front. Plant Sci. 14*, 1293958. https://doi.org/10.3389/fpls.2023.1293958