



Microalgae and Cyanobacteria: How Exploiting These Microbial Resources Can Address the Underlying Challenges Related to Food Sources and Sustainable Agriculture: A Review

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Received: 23 March 2021 / Accepted: 3 November 2021 / Published online: 5 January 2022
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Abstract

For thousands of years, crop production has almost entirely depended on conventional agriculture. However, the reality is changing. The ever-growing population, global climate change, soil degradation and biotic/abiotic stresses are a growing threat to food production and security. Thus, sustainable alternatives to increase crop production for a population projected to reach 9.8 billion by 2050 are a major priority. In addition to vertical and soilless farming, innovative products based on bioresources, including plant growth stimulants, have been a target for sustainable food production. Such solutions have led to the exploitation of microorganisms, including microalgae and cyanobacteria as potential bioresources for food and plant biostimulant products. Microalgae (eukaryotic) and cyanobacteria (prokaryotic) are photosynthetic microorganisms with the capacity to synthesize a vast array of bioactive metabolites from atmospheric CO₂ and inorganic nutrients. The present review outlines the nutritional value of microalgae and cyanobacteria as alternative food resources. The potential aspects of microalgae and cyanobacteria as stabilizers of the net change in soil organic carbon (C) levels for reduced farmland degradation are also highlighted. The applications of microalgae and cyanobacteria as remedies for improved soil structure and fertility, and as enhancers of crop productivity and abiotic stress tolerance in agricultural settings are outlined. This review also discusses the co-cultivation of crops with microalgae or cyanobacteria in hydroponic systems to favor optimum root CO₂/O₂ levels for optimized crop production.

Keywords Microalgae · Cyanobacteria · Food sources · Sustainable agriculture

Introduction

Agricultural production is critically affected by plant diseases, soil quality, global climate change and the exponentially growing population. Global climate change leads to increased weather-related disasters, such as floods and droughts, causing food shortages and famine (Myers et al. 2017). Plant diseases and soil degradation also affect plant growth and development (Teng and Johnson 1988; Savary et al. 2012), leading to reduced crop yield and food production. This scenario threatens food security and is aggravated by the growing population projected to reach 9.8 billion by 2050.

Over the years, the development of chemical products such as synthetic fertilizers and pesticides significantly improved crop productivity. However, the extensive application of such chemical products cause negative impacts on the environment and the ecosystem (Bhandari 2014; Prashar and Shah 2016; Zhang et al. 2018). Thus, modern agriculture

Handling Editor: Wendy Stirk.

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is challenged to search for sustainable food sources and ecofriendly methods of improving crop resilience and productivity. In this context, organic products such as plant biostimulants have been described as sustainable alternatives to improve plant growth, nutrient uptake, nutrient use efficiency, tolerance to abiotic stress and/or crop quality (Calvo et al. 2014; du Jardin 2015). The emerging development of innovative sustainable agricultural products has led to the exploitation of microorganisms including microalgae and cyanobacteria as potential bioresources for food and plant biostimulants (Gonçalves 2021; Alvarez et al. 2021). Microalgae (eukaryotic) and cyanobacteria (prokaryotic) are unicellular microscopic photosynthetic organisms that grow in diverse aquatic habitats and even humid soils (Khan et al. 2018). Microalgae and cyanobacteria have been described as high-nutrient food resources (García et al. 2017). Several species are presently exploited for the generation of protein food supplements and nutraceutical products such as Omega-3, astaxanthin and beta-carotene (Nethravathy et al. 2019; Rahman 2020), making them sustainable alternative food resources with health benefits. In agricultural settings, microalgal and cyanobacterial biomass application to farmlands can stabilize the net change in soil organic carbon (C) levels and reduce farmland degradation. Microalgae and cyanobacteria can also produce bioactive substances such as sulfated exopolysaccharides (EPS) and phytohormones that are beneficial for soil structure and plant growth (Gayathri et al. 2015; Abinandan et al. 2019). Microalgae and cyanobacteria extracts improve plant growth and nutrient uptake, contributing to crop growth and yield (Renuka et al. 2018; Alvarez et al. 2021). Microalgae and cyanobacteria can be grown in hydroponic system substrates, fixing carbon dioxide (CO₂) through photosynthesis and releasing bioactive compounds such as sulfated EPS and phytohormones into the nutrient substrate (Zhang et al. 2017; Barone et al. 2019).

The present review outlines the nutritional value of microalgae and cyanobacteria as sustainable alternative food resources. This review also discusses how the utilization of microalgae and cyanobacteria can be exploited to help restore degrading or abandoned farmlands. The applications of microalgae and cyanobacteria as remedies for improved soil structure and fertility, and as enhancers of crop productivity and abiotic stress tolerance in agricultural settings are outlined. The review also highlights the use of microalgae and cyanobacteria for optimized crop production in hydroponic co-culture systems.

Microalgae and Cyanobacteria

Microalgae and cyanobacteria are microorganisms that exist in various aquatic and terrestrial ecosystems (Rajvanshi and Sharma 2012), and carry out oxygenic photosynthesis,

a high-energy demanding process of water oxidation to molecular oxygen (O₂) and reduction of CO₂ to organic compounds (Tamagnini et al. 2002). Oxygenic photosynthesis first appeared in the ancestors of present-day cyanobacteria more than 3.7 billion years ago. Cyanobacteria are considered among the oldest life forms on Earth and are the original producers of the Earth's oxygenic atmosphere (Saad and Atia 2014). The close association of cyanobacteria with green algae, green plants and other organisms arose more than 1.2 billion years ago from an early endosymbiosis event where a cyanobacterium was taken up into a heterotrophic organism (Björn and Govindjee 2008). Cyanobacteria were originally classified as blue-green algae (Cyanophyta) under botanical codes (Oren 2014a; Demoulin et al. 2019), until their prokaryotic features were established in the 1960s and a proposal was made to include cyanobacteria within the bacteriological code (Stanier et al. 1978). Cyanobacteria in nature are all oxygenic photoautotrophs, with the possible exception of their capacity for facultative anoxygenic photosynthesis (Lau et al. 2015; Garcia-Pichel et al. 2020). Microalgae and cyanobacteria are capable of producing a broad variety of unique, potent substances (Chu and Phang 2019; Kini et al. 2020).

Microalgae and cyanobacteria are suitable bioresources for food and commodities production, and can address the underlying challenges related to food sources and sustainable agriculture (Stephens et al. 2013; Saifullah et al. 2014).

Microalgae and Cyanobacteria are Reliable Food Resources for Human Nutrition

Food security is a major priority worldwide, affecting both developing and developed countries (Rosegrant and Cline 2003; Schmidhuber and Tubiello 2007; Savary et al. 2012). The rapidly growing population will demand 60% increase in agricultural output by 2050, but climate change threatens the current and future agricultural production (Rosenzweig et al. 2014). The human population growth and agricultural intensification are major drivers of environmental degradation. Croplands and pastures are one of the largest terrestrial biomes on the planet, covering ~40% of the land surface and making agricultural production the planet's single most extensive form of land use (Foley et al. 2005). In the tropics, new farmlands are cleared to the detriment of rainforests, savannas and diverse ecosystems (Gibbs et al. 2010; Costantini 2015). Microalgae and cyanobacteria are sustainable resources for food and agricultural product innovation; they are primary producers that exist in various aquatic and terrestrial ecosystems, and require no arable land for production (Rajvanshi and Sharma 2012; Hopes and Mock 2015).

Microalgae and cyanobacteria can produce a broad variety of nutritional value compounds, including proteins,

lipids, carbohydrates, different pigments, vitamins and anti-oxidants. Microalgae are a pivotal food source since their first use by the Chinese 2000 years ago to survive during famine (Mobin et al. 2019). Microalgae species such as *Dunaliella tertiolecta* and *Euglena gracilis* are effective sources of healthy food in Japan (Nethravathy et al. 2019). Cyanobacterial species such as *Arthrospira* spp., also known as Spirulina, have also been used as sources of food by many civilizations. The Aztecs were among the first people who harvested this cyanobacterium in Lake Texcoco within the valley of Mexico (Barrios et al. 2017). Spirulina is rich in proteins (55% to 70% protein content per total dry weight), iron and essential unsaturated fatty acids such as omega 3 (Tokuşoglu and Ünal 2003), and are one of the richest natural green sources of vitamin B12 (Dochi et al. 2010). Spirulina also has various beneficial effects on human health, including antihypertensive effects, prevention of renal failure and the growth of beneficial intestinal *Lactobacillus* bacteria (Beheshtipour et al. 2013). *Arthrospira* spp. are part of the diet of certain human populations where these cyanobacteria grow naturally, such as in the lakes of Chad in Africa (Spolaore et al. 2006; Mata et al. 2010; Hamed 2016), where *spirulina* (locally known as Dihé by the local people) is harvested for food (Fig. 1a and b) (Caterina et al. 2004).

Microalgal species such as *Dunaliella salina* produce β -carotene under stress conditions, which provide numerous benefits for human health (Hosseini and Shariati 2009; Oren 2014b; Wu et al. 2020). β -Carotene is a major carotenoid present in the human diet and the main source of vitamin A in humans (Johnson 2002; Elvira-Torales et al. 2019), but research is still needed for dietary recommendations of algal sourced β -carotene, and caution should be taken for large doses (EFSA 2012). Microalgal species such as *Haematococcus pluvialis* produce astaxanthin, a carotenoid well known for its antioxidant activity as well as anticancer, photoprotection, and anti-inflammatory properties (Yuan et al. 2011). Astaxanthin was approved by the U.S. FDA as an effective nutritional supplement with potent antioxidant properties (Nethravathy et al. 2019). Microalgae and cyanobacteria also produce long-chain polyunsaturated fatty acids (PUFAs) such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) which are effective nutraceuticals with many health benefits (Sathasivam et al. 2019). Table 1 illustrates examples of dietary ingredients produced by microalgal and cyanobacterial species, beneficial for human consumption.

Microalgal and Cyanobacterial Products Market

Microalgal and cyanobacterial biomass production can be used to obtain different kinds of extracts economically important in commerce. Leading commercial players in microalgal and cyanobacterial products include Cyanotech



Fig. 1 Women of Chad preparing (a) and selling (b) spirulina dried on sand, locally known as Dihé by the local people of Chad (Caterina et al. 2004)

Corporation (U.S.), DIC Lifetec Co. Ltd. (Japan), Cellana Inc. (U.S.), Alltech, Inc. (U.S.), Algaetech International Sdn Bhd (Malaysia), BlueBioTech GmbH (Germany) and Parry Nutraceuticals Limited (India) (Algae Products Market Information 2018). The Cyanotech Corporation sources *Arthrospira* sp. food supplements and astaxanthin from natural microalgae *Haematococcus pluvialis*. The current market value of astaxanthin is around \$2,000/kg (Shah et al. 2016; Nethravathy et al. 2019). Although consumed by humans, microalgae-derived astaxanthin is principally consumed by the salmon feed industry (Nethravathy et al. 2019). *H. pluvialis* produced astaxanthin gives salmonids the typical salmon coloration, which is desired by the customers. Major microalgal astaxanthin producers in the market include: Cyanotech corporation (USA), Alga technologies (Israel), Jingzhou Natural Astaxanthin Inc (China), Fuji chemical industry Co. Ltd (Japan), and Parry Nutraceuticals (India) (Shah et al. 2016; Nethravathy et al. 2019).

Other beneficial ingredients such as lutein are commercially marketed in the form of powder, capsules, or oleoresins containing 3% to 80% of lutein (Nethravathy et al. 2019). microalgae-based lutein production provides a promising alternative to marigold petals, the current main commercial

Table 1 Dietary ingredients produced by microalgae and cyanobacteria for healthy food production

Bioactive compounds	Microalgae/cyanobacteria species	References
Astaxanthin	<i>Haematococcus pluvialis</i>	Shah et al. (2016), Li et al. (2020)
Carbohydrates	<i>Porphyridium cruentum</i> and <i>Spirogyra</i> sp.	Chen et al. (2013), Samiee-Zafarghandi et al. (2018)
Essential PUFAs	<i>Cryptocodinium</i> sp., <i>Schizochytrium</i> sp., and <i>Ulkenia</i> sp.	Doughman et al. (2007), Nethravathy et al. (2019)
Exopolysaccharides and carotenoids (B-Carotene)	<i>Dunaliella salina</i>	Pignolet et al. (2013), Koller et al. (2014)
Lipids	<i>Schizochytrium</i> sp., <i>Pavlova lutheri</i> , <i>Chlorella</i> sp., <i>Scenedesmus</i> sp., and <i>Isochrysis</i> sp.	Rodolfi et al. (2009)
Lutein	<i>Chlorella zofingiensis</i> , <i>Chlorella sorokiniana</i> , <i>Muriellopsis</i> sp., <i>Scenedesmus almeriensis</i> , <i>Coccomyxa acidophila</i> , and <i>Chlorella protothecoides</i>	Nethravathy et al. (2019)
Phycocyanin and phycoerythrin	<i>Arthrospira</i> sp. and <i>Porphyridium cruentum</i>	Hsieh-Lo et al. (2019)
Proteins	<i>Spirulina maxima</i> and <i>Chlorella</i> sp.	Garrido-Cardenas et al. (2018), Amorim et al. (2020), Lafarga et al. (2021)
Sterols	<i>Isochrysis galbana</i> and <i>Pavlova lutheri</i>	Ahmed and Schenk (2017), Randhir et al. (2020)
Vitamin C, K, B ₁₂ , A, and E	<i>Chlorella</i> sp., <i>Arthrospira</i> sp., <i>Isochrysis galbana</i> , <i>Porphyridium cruentum</i> , <i>Pavlova</i> sp., and <i>Tetraselmis</i> sp.	Tarento et al. (2018), Jacob-Lopes et al. (2019)

supply of lutein (Fernández-Sevilla et al. 2010; Lin et al. 2015; Xie et al. 2021). Several microalgae species including *Chlorella* spp., *Scenedesmus* spp., *Muriellopsis* spp., and *Dunaliella* spp. produce significant lutein content. However, production of microalgal lutein at commercial scale is still at the laboratory stage and not yet implemented in large-scale commercial production (Lin et al. 2015). Microalgae and cyanobacteria can be dried as food or consumed in the form of capsules and tablets as food supplements (Spolaore et al. 2006; Mata et al. 2010), or incorporated into other food and dairy products, such as pasta, bread, soft drinks, yogurt or snacks (Gross 2004; Mohamed et al. 2013). High value molecules produced by microalgae and cyanobacteria such as DHA and lutein are found in human breast milk and can be incorporated in formulas (Eggersdorfer and Wyss 2018).

Microalgae and cyanobacteria are suitable alternatives for consumers who are increasingly concerned about their health and diet control (Hamed 2016). Illnesses such as high cholesterol and heart disease linked to poor eating habits could be reduced by the substantial consumption of healthy microalgal or cyanobacterial food products due to their high nutrition value (Hamed 2016). For example, β -1,3-glucan polysaccharides, the main component in *Chlorella* spp. are active immunostimulators, free-radical scavenger and reducers of blood lipids (de Jesus Raposo et al. 2015; Sathasivam et al. 2019).

Microalgae and cyanobacteria production and commercialization is often limited by the high cost of cultivation. The optimization of culture medium is an important strategy for increasing the cost-effectiveness of the productions (Ronga et al. 2019). Low-cost resources such as nutrient-rich wastewaters, agricultural by-products and inexpensive

synthetic fertilizers, are effective strategies for increasing the cost-effectiveness of the production (Mata et al. 2010; Gong and Jiang 2011). However, such strategies could not be suitable for algal biomass production destined for human consumption. Microalgae and cyanobacteria cultivation for food production can be grown in controlled optimized conditions to maximally promote the growth rate and productivity (Andrianantoandro et al. 2006; Narala et al. 2016; Tan et al. 2020). Culture parameters in photobioreactors (PBRs) can also be controlled to trigger enhanced production of specific value-added products under artificial growth conditions for the industrialization of microalgae and cyanobacteria (Kothari et al. 2017). Cultivation parameters including pH, temperature, light intensity, nutrient composition and concentration and CO₂ supply are major growth factors of microalgae and cyanobacteria (Renhe et al. 2021; Figueroa-Torres et al. 2021).

Microalgae and Cyanobacteria vs. Crop Plants

Microalgae and cyanobacteria are good sources of proteins, carbohydrates, lipids and several useful metabolites. Microalgae and cyanobacteria do not require arable land (they are cultivated in controlled culture systems) as they can grow in brackish and even seawater, which is unusable for normal agriculture (Masojídek and Torzillo 2014). In addition, the microalgal yield of storable compounds can greatly exceed that of traditional crops. Table 2 illustrates the advantages of cultivation of microalgae and cyanobacteria over crop plants, including higher efficiency of CO₂-fixation and energy conversion, biomass productivity, and lower resources requirements.

Table 2 Advantages of cultivation of microalgae and cyanobacteria in comparison with crop plants

	Microalgae/cyanobacteria	Crop plants	References
CO ₂ -fixation efficiency	Up to 58% in PBRs and 46% in open ponds	Generally, 10 to 50 times lower in terrestrial plants compared to microalgae and cyanobacteria	Chiu et al. (2007), Ramanan et al. (2010), Langley et al. (2012)
Photon conversion efficiency	Ranges from 8 to 10%	Approximately 4.6% for C3 plants and 6.0% for C4 plants at 30 °C. However, it drops to 2.9% and 4.2%, respectively, when measured in the field	Zhu et al. (2010), Bhola et al. (2014), Benedetti et al. (2018)
Biomass production by CO ₂ sequestration	High	Low	Bhola et al. (2014)
Theoretical expected maximal productivity	280 ton of algal biomass (ha) ⁻¹ year ⁻¹ in PBRs and 100 tons ha ⁻¹ year ⁻¹ in open ponds	An average of 10 tons ha ⁻¹ year ⁻¹	Rodolfi et al. (2009), Melis (2009)
Oil production per unit area	30 tons ha ⁻¹ year ⁻¹	4–5 ton ha ⁻¹ year ⁻¹	Chisti (2007) Rodolfi et al. (2009), Mata et al. (2010)
Protein yield per unit area	4–15 ton ha ⁻¹ year ⁻¹	0.6–1.2 ton ha ⁻¹ year ⁻¹ , 1–2 ton ha ⁻¹ year ⁻¹ , and 1.1 ton ha ⁻¹ year ⁻¹ in soybean, pulse legumes, and wheat, respectively	(Van Krimpen et al. (2013)
Land use and water resources	Do not require arable land Grow in brackish and even seawater	Require arable land with a freshwater supply (consume approximately 70% of the freshwater withdrawn per year)	Pimentel et al. (2004), Hüfner (2010), Masojídek and Torzillo (2014)
Resilience to harsh environments	High	Low	Bhola et al. (2014)

Microalgae can be produced at a large scale in artificial open systems (circular and raceway ponds where the culture is directly exposed to open air) or closed systems, where the culture is fully enclosed in a PBR (Narala et al. 2016). Open systems can be divided into natural ponds (eutrophic lakes or small natural basins) and artificial raceway ponds (Hamed 2016). Raceway ponds are the most widely used systems for the commercial production of microalgae (Jerney and Spilling 2018). They are generally the cheapest to construct, and their function is quite simple (Borowitzka 2013; Enzing et al. 2014). They are generally constructed as oval-shaped recirculation channels in which the culture medium flow is guided around bends by baffles placed in the flow channel, and they are stirred with a paddlewheel to ensure culture homogenization, as shown in Fig. 2a. PBRs are reactors that offer a closed-culture environment in which phototrophs are grown or used to carry out photobiological reactions (Tredici 2004) (Fig. 2b and c). PBRs allow better control of culture growth conditions, and most importantly, the microalgae are protected and relatively safe from invasion by competing microorganisms (Vishwanath Patil et al. 2005; Narala et al. 2016).

PBRs are the best culture systems for optimized culture production and biomass quality, despite their high setup, maintenance and energy input costs. In comparison to PBRs, circular and raceway ponds have higher contamination risks, culture evaporation and exposure to weather components, making these culture systems highly dependent on geographical conditions (Kumar et al. 2015; Muhammad et al. 2020). Open culture systems can be a great challenge for countries in the equatorial and monsoon climate regions of Africa but are highly suitable for the warm desert climate of Northern Africa. On the other hand, large-scale microalgal or cyanobacterial production using PBRs may not be practical in most parts of sub-Saharan Africa, considering that the larger population of these regions consists of smallholder farmers (Langyintuo 2020) with less financial capacity for sophisticated large-scale algal production.

Technological Developments in Microalgal and Cyanobacterial Cultivation to Improve the Algal Production and Industrialization

The latest technological developments in microalgal and cyanobacterial cultivation and harvesting, such as automation, phenotyping, and synthetic biology, were described by Fabris et al. (2020). A significant body of research has focused on optimizing conditions that maximally promote microalgae and cyanobacteria growth rates, or trigger enhanced production of specific value-added products under artificial growth conditions for the industrialization of microalgae and cyanobacteria (Andrianantoandro et al. 2006). Figure 3 shows cyanobacterial culture optimization

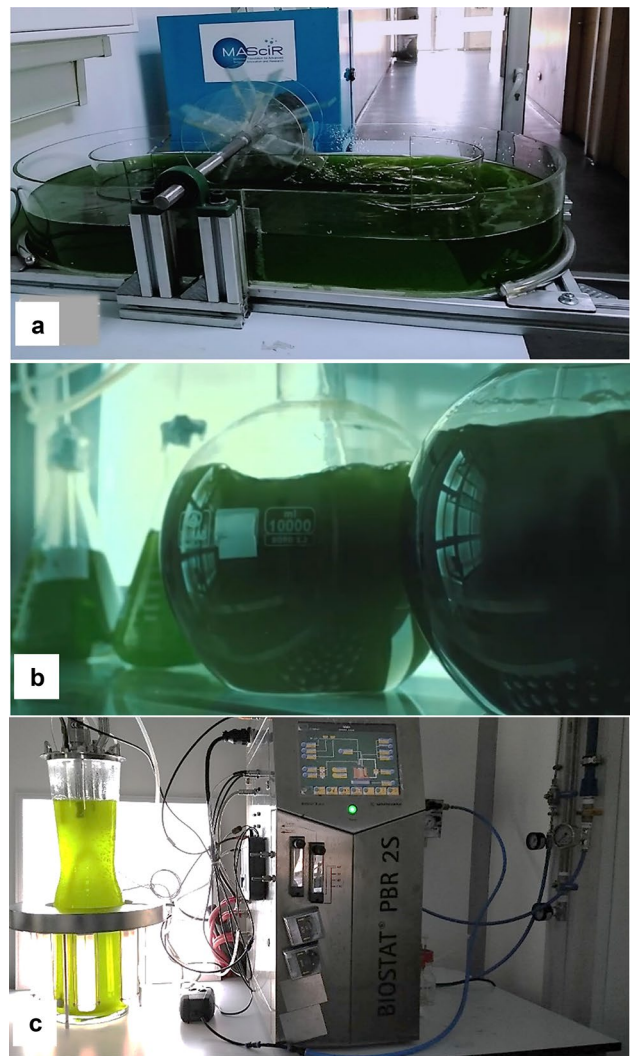


Fig. 2 Raceway pond prototype (a), round flasks (b) and vertical column PBR (c) at the Microalgae Biotechnology Laboratory of the Moroccan Foundation for Advanced Science Innovation and Research (MAScIR)

by manipulating different growth parameters for oriented production of EPS.

The cultivation of microalgae and cyanobacteria has an advantage over heterotrophic systems due to their photosynthetic mechanisms and ability to fix C from inorganic sources (Fajardo et al. 2020). Despite the several advantages and inconveniences reported, there is no single "best practice" method for cultivating microalgae and cyanobacteria, especially at a large scale (Fajardo et al. 2020). The final design of the system is dependent on the final product, the geographical location, and local resources available (e.g., accessibility to water, CO₂, and waste streams) (Fabris et al. 2020).

Advanced molecular techniques for research and development in microalgae are still underdeveloped compared to



Fig. 3 MAScIR exploitation of microalgae and cyanobacteria for research purposes by manipulating different growth parameters for oriented production of EPS. Photo taken at the Microalgae Biotechnology Laboratory of the Moroccan Foundation for Advanced Science Innovation and Research (MAScIR), 2020

fungi, bacteria or even higher plants (Fajardo et al. 2020). Sophisticated studies including the overexpression or down-regulation of several genes in a single organism, are only practically possible in *Chlamydomonas reinhardtii* (Wijffels and Barbosa 2010; Doron et al. 2016; Sanchez-Tarre and Kiparissides 2021). However, new advances in microalgae and cyanobacteria biotechnology are rapidly emerging, paving the way to the establishment of a sustainable, algae-based bioeconomy (Hamed 2016; Fu et al. 2019; Fabris et al. 2020; Fajardo et al. 2020). The available number of full or near-full genome sequences of diverse microalgal species has increased over the last decade (Kumar et al. 2020). Such species include *Chlamydomonas reinhardtii* (Colina et al. 2018; Merchant et al. 2007; Nguyen et al. 2011; Schmollinger et al. 2014), *Chlorella pyrenoidosa* (Duan et al. 2019; Kumar et al. 2020), *Chlorella sorokiniana* (Tejano et al. 2019; Kumar et al. 2020), *Chlorella vulgaris*, *Dunaliella salina* (Yue et al. 2016; Wang et al. 2019; Kumar et al. 2020), *Phaeodactylum tricornutum* (Bowler

et al. 2008; Yang et al. 2014; Longworth et al. 2016) and *Thalassiosira pseudonana* (Armbrust et al. 2004). Genome sequencing of microalgal species will provide a significant genetic resource for the study of their metabolic pathways, regulatory networks, and genetic potentials. Web-based resources such as pico-PLAZA (<http://bioinformatics.psb.ugent.be/pico-plaza/>), AlgaePath (<http://algapath.itps.ncku.edu.tw>) and ALCOdb (<http://alcodb.jp>) are available databases for algal genomics (Kumar et al. 2020). These emerging technologies will provide tools for highly efficient algae-based solutions to a range of societal needs. In-depth understanding of algal biology, genetics and biochemical capacities, will improve both their production and processing for consumption or product innovation in agriculture.

Microalgae and Cyanobacteria for Sustainable Agriculture

Microalgal and Cyanobacterial Biomass Application to Degraded Soils: A New Approach to Restoring Organic Matter on Degraded Farmlands

The conversion of natural ecosystems to agriculture results in the depletion of soil organic C levels, releasing 50 to 100 GT of C from soil into the atmosphere (Lal 2009). This C loss is mainly caused by reductions in the amount of plant roots and residues returned to the soil, and higher soil erosion (Lemus et al. 2005). The soil C deficit created by the depletion of soil organic C stocks represents an opportunity to store C in soil through diverse land management approaches. Naturally, soil organic C levels are based on the interactions between many ecosystem processes, of which photosynthesis, respiration, and decomposition are key. Carbonic matter in degraded soils may take years to restore (Ovsepyan et al. 2019), considering that soil organic C input rates are primarily determined by plant roots and litter deposited from plant shoots (Lemus et al. 2005).

The microalgal and cyanobacterial biomass is rich in organic matter due to the organic C incorporated through photosynthesis, and it is therefore a suitable target for the development of innovative products for soil quality recovery. The total carbohydrate and starch contents of microalgae are approximately 20% and 10% dry weight (DW), respectively (Laurens et al. 2012; Cheng et al. 2017). Cyanobacterial species also have high carbohydrate contents, up to 60% DW. The carbohydrate contents vary with microalgal or cyanobacterial species but can be significantly increased according to cultivation conditions and time (Cheng et al. 2017). The restoration of C storage on degraded land parcels can begin from the decay of microalgae and cyanobacteria organic compounds, that are highly enriched in C (Ontl and Schulte 2012). Other organic compounds produced by microalgae

and cyanobacteria, including proteins and lipids, also contribute to soil organic matter (Ontl and Schulte 2012).

Microalgal and cyanobacterial biomass can also provide soil microbes with energy in the form of C. Although decomposition of this biomass by soil microbes will result in C loss from the soil as CO₂ from microbial respiration, a small proportion of the original C will be retained in the soil through the formation of humus, which is beneficial for soil water retention (Ontl and Schulte 2012; Bastida et al. 2012).

Microalgal and cyanobacterial biomass can boost the productivity of arable land parcels as soil amendments with the capacity to increase soil organic C and stabilize the balance between soil C inputs and outputs in farm soils (Alvarez et al. 2021). Various factors including climate change, historic land use patterns, land management strategies, and topographic heterogeneity influence soil C changes on farmlands, (Ontl and Schulte 2012). Other ecosystem processes, such as soil erosion and leaching of dissolved C into groundwater, can also lead to C loss in soils (Tiefenbacher et al. 2021; Thaler et al. 2021). C inputs from photosynthesis on agricultural farmlands are less than C losses from the soil; therefore, soil organic C levels decrease over time (Ontl and Schulte 2012). Thus, alimentionation of the soil with C-rich products such as microalgal and cyanobacterial biomass could be an important method to stabilize the net change in soil organic C levels. When C inputs and outputs are in balance with each other, there is no net change in soil organic C levels.

Role of Microalgae and Cyanobacteria in Soil Fertility and Structure

Microbes play a vital role in determining soil structure and fertility (Vaishampayan et al. 2001; Singh Jay Shankar 2014; Singh et al. 2016). Although most microalgal species can utilize both organic and inorganic nitrogen (N), they can only assimilate nitrite (NO₂⁻), nitrate (NO₃⁻), and ammonium (NH₄⁺). Cyanobacteria, on the other hand, can convert atmospheric N₂ to ammonia by N₂-fixation (Cai et al. 2013; Ahmed et al. 2014). Cyanobacteria can also tolerate various stresses, such as drought, high or low temperatures, pH and salinity, giving them an advantage over various competitors in different ecological niches (Gröniger et al. 2000; Ibañez et al. 2012; Sand-Jensen and Jespersen 2012). Cyanobacteria in particular have been a specific target in agriculture due to their ability to fix atmospheric N₂ and CO₂ and produce a diversity of biologically active metabolites (Vaishampayan et al. 2001; Singh Jay Shankar 2014; Singh et al. 2016). Cyanobacteria establish symbiotic associations (Subashchandraboise et al. 2011; Hamouda et al. 2016). Certain cyanobacteria species also adapt to local climatic conditions and survive in wet soils (Nisha et al. 2007). Up to 25% of the total biomass of the cyanobacteria surviving in wet soils is

from EPSs (Nisha et al. 2007). EPS significantly contribute to the soil's nutritional status, structural stability and crop productivity. They act as a gluing agent on soil particles, leading to soil aggregation, organic content accumulation, and an increase in the water holding capacity of the top layer of soil (Malam Issa et al. 2001; Nisha et al. 2007). An increase in water holding capacity and organic content favors the growth of plant-growth promoting rhizobacteria (PGPR) (Xiao and Zheng 2016). Therefore, microalgal or cyanobacterial growth in humid soils could subsequently ameliorate soil chemical, physical and biological properties that sustain soil fertility (Flaibani et al. 1989; Zulpa et al. 2003; Paul and Nair 2008).

The aerobic N-fixing capacity of some cyanobacteria makes them important players in the biogeochemical N cycle of both aquatic and terrestrial environments (Garcia-Pichel 2009). Cyanobacteria are a natural component of paddy fields and a beneficial contributor to rice production in tropical countries. Rice production in tropical countries is largely dependent on biological N₂ fixation by cyanobacteria (Vaishampayan et al. 2001), adding approximately 20–30 kg fixed N ha⁻¹ in addition to organic matter to paddy fields (Ahmed et al. 2014; Singh et al. 2016). Cyanobacteria also improve the availability of phosphorus (P) to crops through the solubilization and mobilization of insoluble organic phosphates (Singh et al. 2016; Jhala et al. 2017; Gonçalves 2021).

Microalgal and cyanobacterial biofertilization enhanced the photosynthetic performance and growth of willow (*Salix viminalis* L.) (Grzesik et al. 2017) and rice plants (*Oryza sativum*) (Jochum et al. 2018). The application of microalgal biomass (*Chlorella vulgaris* and *Scenedesmus dimorphus*) to rice plants resulted in significant plant height increase under greenhouse conditions (Jochum et al. 2018), indicating that microalgal biomass can provide a biological option for rice fertility programs. This approach could be especially important for organic rice production where synthetic fertilizers cannot be used (Jochum et al. 2018).

Microalgal and cyanobacterial biomass recovered from wastewater treatments, CO₂ sequestration or biodiesel generation could be valuable in agriculture as organic soil amendments (Ansari et al. 2019). The use of wastewater could provide inexpensive solutions to microalgae and cyanobacteria cultivation, which require significant nutrient input (Renuka et al. 2018). Conversely, agricultural commercialization of microalgae or cyanobacteria biomass generated from wastewater requires thorough quality evaluation and validation. Although wastewaters are rich in nutrients such as organic and inorganic forms of C, N and P, which can be effectively utilized by microalgae, they contain undesirable substances such as heavy metals, pesticides, pharmaceutical compounds, chemicals and pathogens (Rana et al. 2014; Arora et al. 2021). Microalgae and cyanobacteria

accumulate heavy metals. Thus, direct application of wastewater Microalgal or cyanobacterial biomass to the soil may have potential risks on the environment, due to the presence of unwanted hazardous metals, toxins and pathogens (Renuka et al. 2018). Cyanotoxins produced by cyanobacteria can also be absorbed and accumulated by plants, including agricultural food crops, which can have direct negative effect on human and animals (Corbel et al. 2014).

Microalgal and Cyanobacterial Extracts as Biostimulants of Plant Growth and Productivity

Several experimental studies under open-field and greenhouse conditions have demonstrated the plant growth-enhancing capacity of microalgal and cyanobacterial extracts (Garcia-Gonzalez and Sommerfeld 2016; Puglisi et al. 2018; Chanda et al. 2019), indicating their potential use in agriculture as plant growth enhancers.

Crude bioextracts obtained from microalgae and cyanobacteria can ameliorate the growth and development of crops. Liquid extracts of microalgae and cyanobacteria enhanced tomato plant growth through increased chlorophyll content and uptake of N, P and potassium (K) (Chanda et al. 2020). Gas chromatography–mass spectrometry (GC–MS) analysis also showed that treatment with microalgal and cyanobacterial extracts enhanced the production of total lipids and pyridine-3-carboxamide, an amide active form of vitamin B3 (Surjana et al. 2010). The germination of lettuce in 2 and 3 g kg⁻¹ soil with dry microalgal extracts derived from *C. vulgaris* promoted plant growth at the early stages of development (Faheed and Fattah 2008). In the same study, enhanced plant growth based on shoot and root dry weight and length was correlated with improved carotenoid and chlorophyll pigment biosynthesis. Sugar beet seedlings supplemented with extracts of the microalgae *C. vulgaris* or *Scenedesmus quadricauda* also exhibited higher total root length, surface area, and number of root tips (Barone et al. 2018). The different changes in root architecture/morphology induced by the microalgal extracts were attributed to the upregulation of several genes that may intervene in various metabolic pathways (Barone et al. 2018).

The biostimulant activity of microalgal and cyanobacterial extracts is associated with their complex biochemical composition. Biologically active molecules derived from microalgal and cyanobacterial extracts include key amino acids (arginine and tryptophan), sulfated polysaccharides, polyunsaturated fatty acids, vitamins, osmolytes and phytohormones (Ronga et al. 2019; Colla and Rouphael 2020). This complex and multicomponent nature of extracts complicates the study of the mode of action and the production, registration and use of many biostimulants (Yakhin et al. 2017). Studies carried out in evaluating the effect of microalgae and cyanobacteria or their extracts on plant growth and

tolerance mechanisms have been summarized in Table 3. Further studies such as hormone profiling, transcriptomics, proteomics, and metabolomics analysis of treated and untreated plants could also reveal biostimulant activated signaling pathways involved in the stimulation of plant responses (Yakhin et al. 2017).

Cyanobacteria and Microalgae as Biostimulants of Crop Abiotic Stress Tolerance

Crop productivity is often affected by diverse abiotic stresses usually provoked by drought, soil salinization and low or high temperatures. Soil salinization is a major agricultural constraint (Shrivastava and Kumar 2015; Ronga et al. 2019) affecting ~800 million ha globally (Munns and Tester 2008) and is exacerbated by inappropriate chemical fertilization management practices that lead to osmotic imbalance in the soil, affecting crop growth and productivity (Goykovic Cortés and Saavedra del Real 2007). Many studies have highlighted the biostimulant properties of extracts from different microalgal and cyanobacterial species for improving abiotic stress tolerance in higher plants, including salt stress (Rodríguez et al. 2006; Shrivastava and Kumar 2015; El Arroussi et al. 2018).

Dunaliella sp. and *Phaeodactylum* sp. mitigated salt stress in bell pepper (*Capsicum annuum* L.) seedlings by reducing superoxide O₂⁻ production and lipid peroxidation (Guzmán-Murillo et al. 2013). Crude extracts of the cyanobacteria *Arthrospira* sp. and the microalga *Chlorella* sp. improved the salt stress tolerance of wheat (*Triticum aestivum* L.) and enhanced the antioxidant capacity and protein content of grains from treated plants (Abd El-Baky et al. 2010). Extracts from *Nannochloris* sp. also alleviated hydric stress in tomato (*Solanum lycopersicum* L.) as determined by improved root length and increased leaf area and plant height (Oancea et al. 2013). The application of EPS from halophilic microalgae (*Dunaliella salina*) also alleviated the effect of salt stress on the growth of tomato (*Solanum lycopersicum* L.) subjected to high salinity concentrations (3 and 6 g L⁻¹ NaCl) by mitigating the decrease in length and dry weight of the plant's shoot and root systems, and increasing K uptake and the K⁺/Na⁺ ratio (El Arroussi et al. 2018). In the same study, the accumulation of proline, phenolic compounds and Na⁺, as well as catalase (CAT), peroxidase (POD) and superoxide dismutase (SOD) activities triggered by salt stress, were attenuated after EPS treatment. Metabolic pathways involved in the plant's tolerance to stress, such as jasmonic acid-dependent pathways, were also enhanced.

Microalgal or cyanobacterial biostimulants are usually applied as total crude extracts containing diverse organic compounds, including hormones. This mixture of diverse organic compounds could contain molecules mimicking compatible solutes, signaling molecules or elicitors; hence,

Table 3 The effect of microalgae and cyanobacteria (or their extracts) on soil fertility, and mechanisms of plant growth and salt stress tolerance

Microalgal and cyanobacterial species	Crop	Observed effects	References
Effects of microalgae and cyanobacteria on soil improvement			
<i>Nostoc</i> sp.		EPSs act as a gluing agent on soil particles, leading to soil aggregation Increase in the organic content accumulation and water holding capacity of the top layer of soil Increase in organic carbon content in the soil	Maqubela et al. (2008), Parwami et al. (2021) Karthikeyan et al. (2007)
<i>Calothrix ghoesei</i> , <i>Hapalosiphon intricatus</i>	<i>Triticum aestivum</i> L.	Increase in the availability of N in the soil by N ₂ fixation	Swarmalakshmi et al. (2013)
Microalgae and cyanobacteria as biofertilizers			
<i>Anabaena torulosa</i>	<i>Triticum aestivum</i> L.	Increase in N ₂ fixation Increase in nutritional value of pea seeds Increase in growth parameters and photosynthetic pigments	Osman et al. (2010)
<i>Nostoc entophyllum</i> and <i>Oscillatoria angustissima</i>	<i>Pisum sativum</i>	Increase in N availability in the soil Increase in grain and straw yields	Jha and Prasad (2006)
Cyanobacterial inoculum of: <i>Aulosira fertilissima</i> , <i>Anabaena sphaerica</i> , <i>Nostoc hatei</i> , <i>Cylindrospermum majus</i> and <i>Westitloopsis prolifica</i>	<i>Oryza Sativum</i>	Increase in N and P availability in the soil Improvement of nutritional properties	Nisha et al. (2007)
Cyanobacterial consortia of: <i>Anabaena doliolum</i> , <i>Cylindrospermum sphaerica</i> , and <i>Nostoc calcicola</i>	<i>Pennisetum glaucum</i> <i>Triticum aestivum</i>	Increase in N, P and K availability in the soil Increase in organic carbon content in the soil Increase in N, P and K contents in roots, shoots and grains	Renuka et al. (2018)
Effects of microalgae and cyanobacteria (or their extracts) on nutrient uptake			
Microalgal–cyanobacterial consortia of: <i>Chlorella</i> sp., <i>Scenedesmus</i> sp., <i>Chlorococcum</i> sp., <i>Chroococcus</i> sp., <i>Phormidium</i> sp., <i>Anabaena</i> sp., <i>Fischerella</i> and <i>Spirogyra</i> sp.	<i>Triticum aestivum</i> L.	Enhanced nutrient uptake via increased root length	Chanda et al. (2020)
<i>Chlorella ellipsoidea</i> , <i>chlorella pyrenoidos</i> and <i>Arthrospira maxima</i>	<i>Solanum lycopersicum</i> L.	Increase in germination rate and plant yield Increase in fresh and dry weights of shoot, root and whole plant Increase in shoot length and in the number of leaves	Dineshkumar et al. (2017)
Effects of microalgae and cyanobacteria (or their extracts) on plant growth			
<i>Chlorella vulgaris</i> and <i>Arthrospira platensis</i>	<i>Zea mays</i>	Enhanced seedling growth by root-promoting hormones (auxins, cytokinins and gibberellic acid) Higher total root length, surface area, and number of root tips	Karthikeyan et al. (2007) Barone et al. (2018)
<i>Calothrix ghoesei</i> , <i>Hapalosiphon intricatus</i> and <i>Nostoc</i> sp.	<i>Oryza sativum</i>	Enhancement of soluble carbohydrate, soluble protein and total free amino acids	Faheed and Fattah (2008)
<i>Chlorella vulgaris</i> and <i>Scenedesmus quadricauda</i>	<i>Beta vulgaris</i> L.	Enhanced photosynthetic performance and growth	Grzesiek et al. (2017), Jochum et al. (2018)
<i>Chlorella vulgaris</i>	<i>Lactuca sativa</i> L.	Reduced production of superoxide radicals Low lipid peroxidation	Guzmán-Murillo et al. (2013)
<i>Chlorella vulgaris</i> and <i>Scenedesmus dimorphus</i>	<i>Salix viminalis</i> L., <i>Oryza sativum</i>		
Effects of microalgae and cyanobacteria (or their extracts) on abiotic stress			
Extracts from <i>Dunaliella</i> spp. and <i>Phaeodactylum</i> spp.	<i>Capsicum annuum</i> L.		

Table 3 (continued)

Microalgal and cyanobacterial species	Crop	Observed effects	References
<i>Spirulina</i> spp. and <i>Chlorella</i> spp.	<i>Triticum aestivum</i> L.	Enhanced antioxidant capacity and protein content of the whole grains	Abd El-Baky et al. (2010)
Nannochloris sp.	<i>Solanum lycopersicum</i> L.	Alleviated effects of water stress through enhanced plant growth and nutrient uptake	Oancea et al. (2013)
Exopolysaccharides from <i>Dunaliella salina</i>	<i>Triticum aestivum</i> , <i>Solanum lycopersicum</i> L.	Improved seed germination and seedling growth Enhanced plant size and K uptake	El Arroussi et al. (2016); El Arroussi et al. (2018)
Effects of microalgae and cyanobacteria (or their extracts) on biotic stress	<i>Solanum lycopersicum</i> L.	Improved carotenoid, chlorophyll and proteins content Improved Nitrate Reductase (NR), NAD-Glutamate Dehydrogenase (NAD-GDH) activities in plant leaves	Farid et al. (2019), Rachidi et al. (2021)
<i>A. platensis</i> , <i>D. salina</i> and <i>Porphorydium</i> sp.		Increase in the activity of β -1,3 endoglucanase in shoots and roots	Senthil-Kumar et al. (2013)
<i>Anabaena laxa</i> and <i>Calothrix elenkinii</i>	<i>Coriandrum sativum</i> , <i>Cuminum cyminum</i> , <i>Foeniculum vulgare</i>	Increase in fungicidal activity Increase in germination rates Increase in shoot and root length Increase in plant dry weight	
Effects of microalgae and cyanobacteria in hydroponics			
<i>Chlorella vulgaris</i>	<i>Eruca vesicaria</i> , <i>Lactuca sativa</i> , purple kohlrabi	Improved removal rate of total dissolved solids, total N, and total P of the nutrient solution	Huo et al. (2020)
<i>Chlorella infusioenum</i>	<i>Solanum lycopersicum</i> L.	Increased supply of O ₂ into the nutrient solutions by photosynthesis	Zhang et al. (2017), Barone et al. (2019)
<i>Scenedesmus quadricauda</i>		Improved crop root respiration and growth	
<i>Chlorella vulgaris</i>			

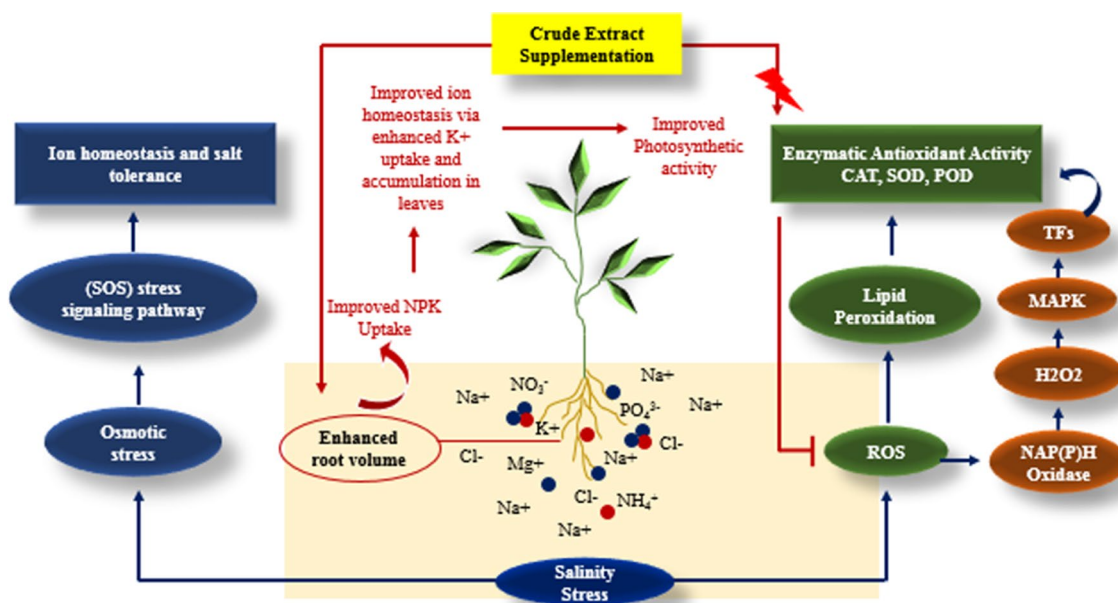


Fig. 4 Possible biostimulant effects of Microalgae-cyanobacteria Extract Formulation (MEF) on salt-stressed tomato plants. MEF enhances root growth, which favors nutrient uptake and consequent ion homeostasis in leaves and photosynthetic activity. MEF stimulate

antioxidative enzymes, which consequently attenuate lipid peroxidation in plant cells. Reactive Oxygen Species (ROS), Hydrogen Peroxidase (H_2O_2), Catalase (CAT), Peroxidases (POD), Superoxide Dismutase (SOD), and Salt Overly Sensitive pathway (SOS)

they could have multiple direct or indirect effects on plant growth and stress tolerance (Renuka et al. 2018; Colla and Rouphael 2020). Figure 4 illustrates the possible biostimulant effects of Microalgae-cyanobacteria Extract Formulation (MEF) on salt-stressed tomato plants. Bioactive organic compounds in MEF can stimulate the antioxidative enzyme system, and consequently attenuate lipid peroxidation in plant cells. MEF can also enhance root growth, which favors nutrient uptake and consequent ion homeostasis in leaves and photosynthetic activity.

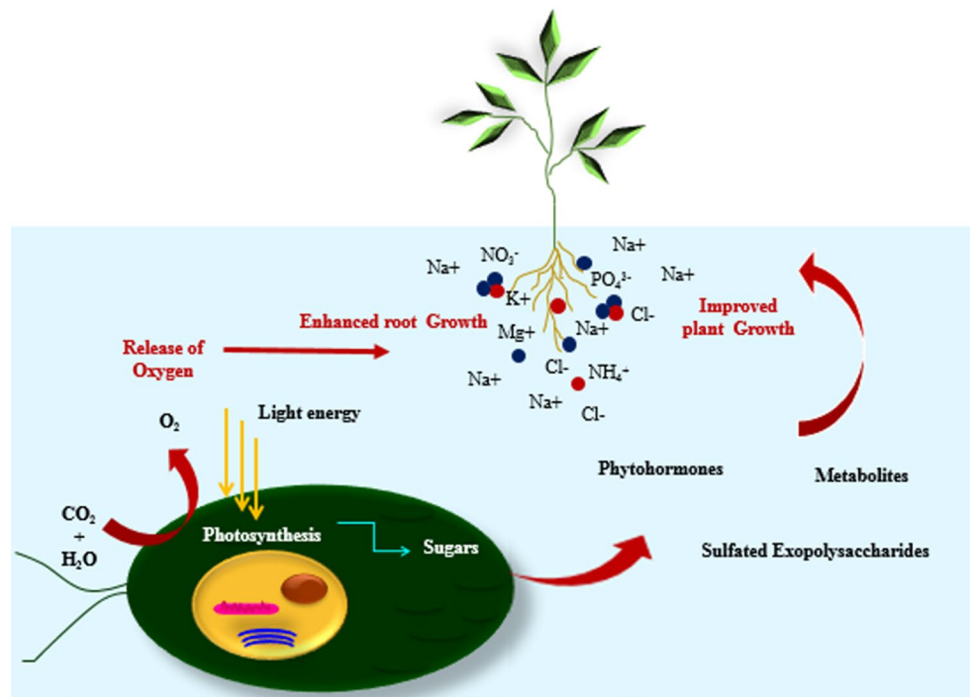
Co-cultivation of Microalgae/Cyanobacteria and Plants in Hydroponic Systems: An Emerging Innovative Method for Biologically Stimulated Crop Growth and Productivity

Soilless cultivation (hydroponics) is the future for agricultural production sectors. Research studies such as those on NO_3^- management or crop quality increases by managing the electrical conductivity of the solution are commonly exploited in hydroponics. Emerging new and innovative methods, such as the use of nanoparticles and beneficial microorganisms, including PGPRs, have also been described. Crop co-cultivation with microorganisms such as microalgae or cyanobacteria in hydroponics can ameliorate plant growth. Microalgae and cyanobacteria produce and release a wide range of bioactive compounds in the culture solution.

In hydroponics, microalgae and cyanobacteria can be grown in the nutrient solution. The release of bioactive compounds such as EPS and other metabolites in the substrate solution may trigger mechanisms related to plant tolerance, productivity and vigor (Fig. 5). Soil application of EPSs obtained from *D. salina* mitigated the effect of salinity stress by enhancing reactive oxygen species (ROS)-scavenging enzyme activities, phenolic compounds and key metabolites involved in antioxidative stress mechanisms (El Arroussi et al. 2018). Hydroponic co-cultivation of tomato plants with microalgae also stimulated crop performance and growth in terms of fresh and dry plant weight by ameliorating the substrate solution (Zhang et al. 2017; Barone et al. 2019). The plant growth stimulation was attributed to the constant use of CO_2 and delivery of O_2 to the hydroponic nutrient solution, through microalgal photosynthesis (Barone et al. 2019). The lower CO_2 levels, resulting from CO_2 fixation by microalgae or cyanobacteria, and the liberation of O_2 in the root zone of hydroponically grown plants can positively regulate plant growth. CO_2 accumulation in an O_2 -deficient root zone can be a detrimental factor to certain crop plants in flooded fields or aeroponic systems (Boru et al. 2003a, b).

Crop co-culture with photosynthetic microorganisms in hydroponics releases more O_2 in the nutrient solution to favor optimum root CO_2/O_2 levels for plant growth. The sole accumulation of CO_2 in the root zone does not negatively affect plant growth unless O_2 is deficient. Plant roots are naturally colonized by microorganisms and

Fig. 5 Possible biostimulant effects of hydroponics co-cultivation with microalgae or cyanobacteria on crops. Bioactive metabolites such as sulfated exopolysaccharides and phytohormones released in the substrate solution enhance plant growth. CO_2 fixation and O_2 release from photosynthesis by microalgae or cyanobacteria in the substrate solution ameliorate root respiration



evolve more CO_2 (CO_2 concentrations in the rhizosphere is > 10-fold higher than in the atmosphere) (He et al. 2010). Exposure to no O_2 combined with elevated CO_2 levels attaining 30% (v/v) of total dissolved gases caused severe necrosis and stunted growth in soybean plants (Boru et al. 2003b). These results indicate that the co-culture technique could especially benefit crop plants with lower tolerance to higher dissolved CO_2 in O_2 -deficient media.

The co-cultivation of crops with Microalgae or Cyanobacteria in hydroponic systems has been studied for several years (Hultberg et al. 2013; Ronga et al. 2019; Huo et al. 2020; Ergun et al. 2020; Supraja et al. 2020) as a new emerging innovative method for biologically stimulated crop growth and productivity. A plant-microalgae consortia relatively increased the pH and dissolved O_2 from microalgae photosynthesis, and significantly improved the removal rate of total dissolved solids, total nitrogen (TN), and total phosphorus (TP) of the nutrient solution (Huo et al. 2020). Aqueous extracts prepared from microalgae collected from a greenhouse hydroponics solution significantly inhibited the growth of *Fusarium oxysporum* on slow nutrient agar (Schwarz and Gross 2015). Conversely, Lettuce fresh weight, shoot/root ratio, water and N uptake were significantly reduced in the presence of the microalgae *Chlamydomonas* spp. and *Scenedesmus* spp., compared to treatments which excluded microalgae (Schwarz and Gross 2015).

Commercial crop co-cultivation with photosynthetic microorganisms may have limiting factors. Co-cultivation will require optimized nutrient solution for the growth of

both crops and microalgal or cyanobacterial species. The source and concentration of N can affect the growth and biochemical composition of microalgal and cyanobacterial species (Ronga et al. 2019). Several factors such as nutrient composition and concentration, light intensity, pH and electroconductivity (EC) affect the growth and the chemical composition of the microalgae or cyanobacteria (Danesi et al. 2002; Colla et al. 2007; Ogbonda et al. 2007). Crop co-cultivation with photosynthetic microorganisms is also limited to soft water microalgal or cyanobacterial species, as many crops poorly develop in highly saline sea water (Shrivastava and Kumar 2015). Hydroponic containers made of opaque material influences the growth of microalgae or cyanobacteria (Tocquin et al. 2003; Bawiec et al. 2019). In industrial setups, the hydroponic system could be mounted with a compartmentalized PBR, containing the photosynthetic microorganism and nutrient solution, and connected to the plant growth tray made of opaque material for optimized root growth, as illustrated in the drip system and nutrient film technique by Lee and Lee (2015). Challenges resulting from pH changes and growth of mold in the reservoir or tubing system can also be overcome by the use of non-recovery drip system. In this system, the hydroponic nutrient solution in the reservoir is delivered to each plant or pot using a pump, with the amount of nutrient solution for each plant adjusted by an electronic timer (Lee and Lee 2015). The nutrient solution is not collected and returned to the reservoir for recirculation through the system, thereby preventing fungal growth and pH changes (Lee and Lee 2015).

The biostimulant effects of microalgae or cyanobacteria in hydroponics may depend on a wide range of factors, including microalgae-excreted metabolites and phytohormones and O₂/CO₂ ratio changes in the root zone (nutrient solution). Analyzing all these factors will allow better exploitation of these microorganisms in developing microalgal and cyanobacterial biotechnology. Furthermore, hydroponic waste solutions contain high nutrients (Lee and Lee 2015). Thus, microalgae and cyanobacteria can be an effective method of removing nutrients from hydroponic waste solution, before they are discharged. The use of microalgae or cyanobacteria will prevent the generation of waste materials and hydroponic waste solution. The resulting biomass can be valorized in agriculture as soil conditioners, biostimulants or biofertilizers.

Conclusion

The rapidly growing population and climate change require further innovation to address the practical limitations and serious environmental concerns associated with current agricultural practices. Microalgae and cyanobacteria are targets for next-generation sustainable bioresources. They can be utilized to produce value-added bioproducts, and their rapid growth rates and higher biomass productivity offer several advantages over terrestrial crops. Microalgae and cyanobacteria can also be utilized in agricultural settings as soil conditioners and biostimulants of plant growth and abiotic stress tolerance.

Mass cultivation and commercial production of microalgae and cyanobacteria are highly dependent on the economics of their biomass production. The utilization of waste-substrates for the production of microalgal and cyanobacterial biomass is an economically viable strategy. Conversely, challenges associated with waste generated biomass, such as the presence of unwanted hazardous metals, toxins and pathogens still require thorough studies and field scale evaluation before their commercialization. In-depth studies of the biostimulatory effects of microalgal and cyanobacterial extracts on plant growth-related parameters will also facilitate their production and processing for product innovation in agriculture. Technological developments in microalgal and cyanobacterial cultivation and harvesting, such as automation, phenotyping, and synthetic biology will provide tools for highly efficient algae-based solutions to meet a range of societal needs. Genetic manipulation, such as the overexpression or downregulation of several genes in a single organism, is also possible in the microalga *Chlamydomonas reinhardtii*, and is a practical method to improve product development of microalgae and cyanobacteria for large scale production.

Author Contributions CMJ conceived the idea and wrote the first draft of the manuscript. CMJ designed the figures and drafted the table. EH contributed to manuscript revision, content modifications, scientific review and approval of the final version. All authors read and approved the final manuscript.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval Not applicable.

Consent for Publication Not applicable.

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