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Microalgae: A Revolutionary Bio-agents For Sustainable Agriculture

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Abstract: *Holding an opinion, the challenges involving agro-ecosystem and environment, the recent development in biotechnology offers a more reliable approach to address the food safety for imminent generations and resolve the intricate environmental problems. Microalgae are one of the most diverse groups of gram-negative photosynthetic prokaryotes. Many members of the Micro algae possess the ability to fix molecular nitrogen. This property, combined with their photosynthetic habit of life, places these algae among the most completely autotrophic living organisms. Microalgae are the most successful and sustained prokaryotic organism during evolution. Microalgae considered as one of the primitive life forms found on our planet. Several unique features of Microalgae such as oxygenic photosynthesis, high biomass yield, growth on non-arable lands and a wide variety of water sources (contaminated and polluted waters), generation of useful by-products, enhancing the soil fertility and reducing green-house gas emissions, have collectively offered these bio-agents as the precious bio-resource for sustainable development. Further nitrogen fixing capacity of cyanobacteria has attracted agriculturists and researchers and they used Microalgae biomass as the effective bio-fertilizer source to improve soil physico-chemical characteristics such as water-holding capacity and mineral nutrient status of the degraded lands. This review is an effort to enlist the valuable information about the qualities of Microalgae and their potential role in the agricultural for the future welfare of the planet.*
Key Word*: Microalgae, Technologies, Bio-fertilizer; Bio-stimulant, Bio-pesticides; Biomass*

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I. Background

The world population, which accounted six billion in 1999 rose to seven billion in 2011 and is estimated to touch up to nine billion by 2050. With over increasing population, the need for resources is also increasing, which in turn increases our dependency on agricultural crops [1]. Hence, whilst farmers are called to increase agricultural production along with issues related to climate change, researchers must be called to develop innovative products and technologies able to increase crop yields and quality, while decreasing their agricultural carbon footprint [2]. On the other hand, the social and economic activities developed by this increasing population have contributed to [1]: (i) a reduction in the area available for the production of food crops; (ii) water resources degradation and scarcity; (iii) accumulation of xenobiotic compounds in the soils; and (iv) degradation of soils' quality and fertility. One major field of application is the use of seaweed and microalgae in agriculture. They can elicit defensive responses resulting in protection against pathogen or insect damage, and can be used as biofertilizers (Chatzissavvidis and Therios, 2014). Biofertilizers are gaining significance in sustainable agriculture as a means of enhancing crop productivity, in an environmentally friendly and economically viable manner, and reducing the polluting effects of synthetic fertilizers. To overcome the challenges related to the increase in global population and anthropogenic activities and meet the requirements for food supplies, an improvement in the productivity and sustainability of agricultural practices is required [4]. Chemically-based products have been widely used in agriculture, either as plant growth promotors (improving crops' yields), or as plant protection agents (protecting plants from different stress conditions) [4, 5]. However, most of these agents are toxic and their accumulation in the plants and in the soil can be a threat to humans and to the environment. Moreover, their accumulation has been associated with the development of microbial resistance to several drugs [5,6]. Considering the negative impacts of these products, current regulations are limiting the use of mineral fertilizers and chemical products in agriculture [5,6]. In the search for more justifiable and environmentally friendly solutions to improve agricultural productivities, researchers have focused their attentions on biologically based products, with microalgae and cyanobacteria emerging as a valuable resource for crops' production and protection due to their bio-fertilizing and bio-stimulating potential [5,6].

Microalgae are classified mainly considering their pigmentation, life cycle and cell structure. It was estimated that ~800,000 microalgae species exist, of which ~50,000 species are described [6]. This high number of species might provide a wide range of possible uses. In fact, is possible to select different strains having different biochemical compositions and which are able to grow in different environments [7]. Generally, algae are classified mainly depending on their color, shape, and life cycle [8]. Algae are broadly classified as micro- and macroalgae based on size. Macroalgae indicates large aquatic photosynthetic plants that can be seen without the aid of a microscope and can generally be divided into three groups: Green (Chlorophyta), Red (Rhodophyta), and Brown-Kelps (Phaeophyta—related to Chromista). Microalgae comprise representative genera, including *Arthrospira, Chlorella, Dunaliella, Nostoc*, and *Aphanizomenon [8]*. Prokaryotic microalgae, namely, cyanobacteria, play a critical role in the natural ecosystem, particularly in plant–microbe interactions. However, the idea that algae are a member of the plant-associated microbial community has long been debated [8,9].

The use of Microalgae in agriculture dates from thousands of years ago [5]: for example, in coastal areas of Europe, farmers used to apply algae harvested near the shore in their cultures, both directly or after composting, observing positive effects in soil fertilization. Since this period, algal biomass has been extensively used in agriculture, but in the 20th century, products obtained from algal extracts have attracted the attention of farmers worldwide [5]. In fact, a wide variety of biologically-active compounds extracted from algae and cyanobacteria (e.g., phenols, terpenoids, free fatty acids—FFAs, polysaccharides, and carotenoids) has demonstrated to have promising effects in crops' production [10]. According to the literature, algal metabolites can play an important role in [4]: (i) soil decontamination and fertilization; (ii) plant protection against biotic and abiotic stress factors; and (iii) plant development. In addition, microalgae and cyanobacteria also present phytohormones, which are known for their activity as plant-growth promotors [11]. Considering their ability for the improvement of a green agriculture, both biomass and extracts from microalgae and cyanobacteria are commercially available. Moreover, microalgae showed to have potential application as bio-stimulants and bio-fertilizers [12]. Nowadays, the use of microalgae in agriculture productions, especially as Bio-stimulant or Bio-fertilizers, is attracting the interest of growers and agrochemical industries aiming to improve the sustainability of crop production [13].

Considering all the aspects presented, the research on microalgae for agriculture is a very relevant and promising topic. This manuscript presents an overview of how Microalgal biomass and extracts can helps to improve agriculture sustainability.

II. Microalgal Technologies

Considering all the aspects presented, the research on microalgae for agriculture is a very relevant and promising topic. This manuscript presents an overview of how Microalgal biomass and extracts can helps to improve agriculture sustainability. Controlled production of microalgal biomass is a fast-growing technology, as microalgae can be used to produce a wide range of commercially valuable cellular metabolites, including high-quality proteins, lipids, carbohydrates, dyes, and vitamins for the food/feed industry and the broad cosmetic industry (Table 1) [14]. Systems for producing algal biomass feature high technological efficiency, owing to the significant photosynthesis efficiency of algae and the relatively fast growth of algal biomass [15]. Phototrophic cultivation of microalgae in photobioreactors can process waste from industrial and municipal sources, which means that commercial microalgae cultivation systems can be constructed on land unsuitable for agricultural use, near heating/cogeneration plants, sewage treatment plants, and other industrial facilities that produce carbon dioxide and biogenic compounds [14]. Despite the demonstrated utility of microalgal biomass-based systems for the bioenergy industry, most industrial microalgae cultivation plants established and extensively described in the literature deal mainly with the production of high-quality feed/food additives, precious dyes, or fertilizing substances (Table 1), due to the difficulties in conclusively assessing and balancing methods for microalgal biomass production and technologies for converting it to energy carriers. The commercialization of technology and its transfer from laboratory conditions to a technical scale requires extensive research, conceptual, operational, and marketing works that allow the product to be finally placed on the market. Although relative studies present various models of knowledge and technology commercialization, they also show some similarities, as they involve a certain repetitive group of activities [14]. An important element in the process of making investment decisions regarding the commercialization of innovative products is to assess the maturity of new technologies. This assessment, called "technology readiness assessment" (TRA), should take into account the state of work on the development of a new product/technology, prospects for further development, the amount of funds necessary to invest, and innovative risk.

Table no 1 : Applications of microalgal technologies

Agar	Food ingredient, fruit preserves, hydrocolloids, clarifying brewing agent, paper industry, and others
Alginate	Food additive, medical, pharmaceutical, paper, cosmetic and fertilizer industries, textile printing
Antioxidants	Preservatives in cosmetic, chemical, food, and pharmaceutical industries
Astaxanthin	Food supplement as food dye additive and antioxidant
Beta-carotene and carotenoids	Precursor for vitamin A and supplement for vitamin C, food additive as coloring agent, and antioxidant
Bioenergy and biofuels	Biodiesel, bioethanol, biogas, biohydrogen, biomethane, aviation gas, biobutanol, biosyngas, bio-oil, gasoline, solid fuel, jet fuel
Biochar	Agricultural and sorbent uses, combustion
Biorefinery	Various chemicals and biofuels
Biosorbent	Ion exchange materials that bind strongly heavy metal ions
Biogas upgrading	Biological sequestration of CO_2 with photosynthetic microalgae (photosynthesis allows producing biogas with 94% methane content)
Carragen or carrageenan	Pet food, food additive, gels, toothpaste
Catalysts	Catalytic properties
Chemicals	Industrial and medicinal uses
Conditioners	Chemical, cosmetic, and farming industries
Digester residue	Compost or vermicompost
Extraction of Proteins	Fertilizers, industrial enzymes, animal/fish feeds, surfactants, bioplastics
Feed	Animal food
Fertilizers	N-, P-, and K-rich fertilizers
Gas treatment	Reducing emissions of carbon dioxide and other pollutants (nitrogen and sulfur oxides) from waste and exhaust gases
Phytosterol	Food supplements
Pigments	Natural colorants in paper and textile industries
Production of Therapeutics materials	Pharmaceutical industry
Waste management	Use of waste glycerol as a carbon source in heterotrophic cultivation
Waste water treatment	Nitrogen and phosphorus removal from municipal wastewater
Waste water treatment	Biodegradation of sparingly degradable pollutants
Waste water treatment	Treatment of organic wastewater

III. Microalgae as a potential source of Bio-stimulant, Bio-fertilizer and Bio-pesticides

The major proportion of the population would be contributed by India (DESA UN, 2015). Increment in population has directly and indirectly dependent on the demand for contamination-free healthy food. Microalgae and cyanobacteria are an important source of biologically-active compounds, such as phenolic compounds, polysaccharides, hormone-like substances and proteins, known for their benefits as antioxidant agents, plant-growth promotors, among others. Moreover, living organisms, both prokaryotes (e.g., nitrogen-fixing cyanobacteria) and eukaryotes (e.g., microalgae and macroalgae/seaweeds), are broadly recognized for their role in soils' fertilization and plant growth stimulation [13]. Besides these important characteristics, the production of microalgal/cyanobacterial biomass can be quite advantageous, when compared to the production of other biological resources [7,13]: (i) production of these photosynthetic organisms can be performed in non-arable areas, thus not competing with the areas intended for food production; (ii) microalgae and cyanobacteria can be grown in low-quality waters, such as wastewaters, thus reducing the requirements for freshwater and nutrients (mainly nitrogen and phosphorus); (iii) the wealth composition of microalgal/cyanobacterial biomass can be fully exploited towards the induction of multiple responses in the same crop; and (iv) when growing autotrophically, microalgae and cyanobacteria uptake CO_2 from the atmosphere, thus reducing the carbon footprint of agricultural practices. Although several products can be used in the improvement of crops' productivities, it is important to understand that different biological compounds may improve the agricultural productivities through different modes of action: (i) soils' improvement; (ii) crops' protection against biotic and abiotic stress factors; and (iii) direct growth stimulation. Considering these roles, microalgal/cyanobacterial products and biomass can be classified as biofertilizers, bio-stimulants and biopesticides. Figure 1 summarizes the main activities associated to these biologically-based products in the development of agricultural practices, highlighting their action mode and effect on crops' production.

Bio-fertilizers are biological based compounds that promote and improvement in crops' productivities through their activity at the soil level. Typically, these compounds and/or microorganisms are responsible for the improvement of soil properties and soils' fertility, providing the essential nutrients (e.g., nitrogen, phosphorus and potassium) for plants' growth [16,17]. Depending on their beneficial effects and on the microorganisms integrating these formulations, bio-fertilizers can be classified as [16]: (i) plant growth-promoting bacteria; (ii) compost; (iii) nitrogen-fixators; (iv) phosphate- and potassium-solubilizing bio-fertilizers; and (v) phosphorus-mobilizing bio-fertilizers. The use of bio-fertilizers in agriculture presents several advantages, such as [5]: (i) increased crop productivities per unit of area and time; (ii) reduced energetic requirements; (iii) control and maintenance of adequate soil properties and fertility; (iv) lower risks of soil and water contamination; and (v) crops' protection against pathogenic organisms.

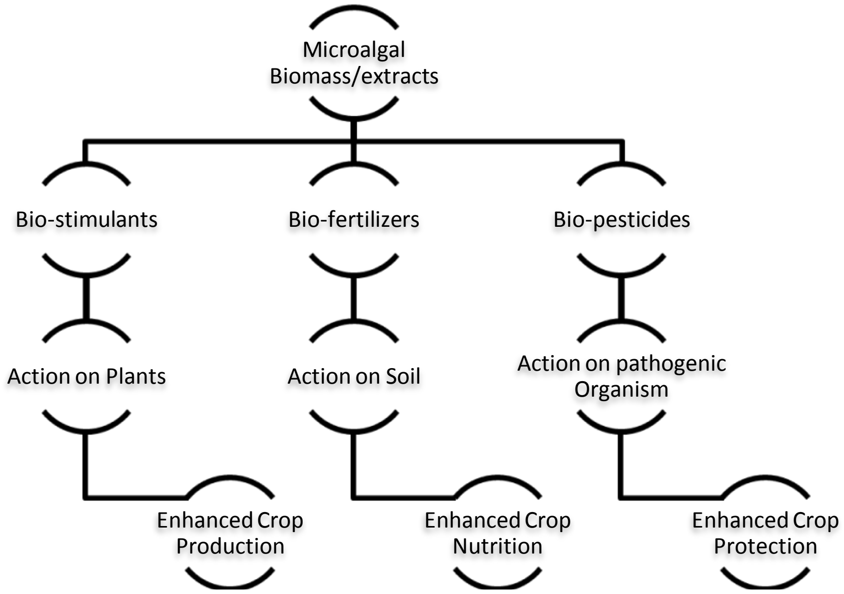

Figure 1. Cataloguing of the main activities attributed to Microalgal biomass and extracts in crops cycle

Bio-stimulants promote crops' productivity by acting directly on the plant. These compounds are responsible for improving respiration, photosynthetic activity, nucleic acid synthesis and ion uptake, enhancing plants' metabolism and, hence, plants' growth [5]. The stimulatory activity of bio-stimulants can be observed under both optimal and adverse conditions, meaning that these compounds can play an important role in the improvement of plants' resistance and tolerance against stress conditions [7,13]. The application of bio-stimulants in agriculture has, therefore, the following advantages [7,13]: (i) increased crop productivities; (ii) increased nutrients' utilization efficiencies; and (iii) enhanced crops' quality. Characterization and categorization of bio-stimulants can be quite complex, as a wide variety of compounds (e.g., polysaccharides, phenolic compounds, hormone-like compounds, vitamins, etc.) have been identified for their bio-stimulating activity in crops. Microalgae-derived products have multi-functional properties in agriculture, facilitating nutrient uptake, improving crop performance, physiological status and tolerance to abiotic stress [18]. Microalgae-based plant bio-stimulation could be attributed also to the modulation of microbial communities residing in both the phyllosphere and the rhizosphere [18]. For instance, inoculation with blue-green algae such as *Calothrix elenkinii* stimulated the phyllosphere and rhizosphere microbiomes [19]. One of the main mechanisms responsible for the improvement of soil microbial communities in response to inoculation with blue-green algae relates to the production of exopolysaccharides. Exopolysaccharides secreted by many microalgal species provide organic carbon for the growth and development of beneficial microbes, leading to the formation of useful biofilms in the rhizosphere [20]. Their association with soil elements helps in the solubilization, mineralization, and bioavailability of macro and micronutrients, thus improving crop performance [21]. The application of aqueous extracts of Chlorella ellipsoida and Spirulina maxima on wheat and Nannochloris on tomato also mitigated salt stress impact [13]. Microalgae biomass showed to contain micro- and macronutrients, especially N, phosphorous (P), and K, and might be considered as an organic slow-release fertilizer [4]. Analysis of *Arthrospira* spp. dry biomass revealed that it contains 6.70, 2.47 and 1.14% on dry base of N, P and K, respectively [22], while, the calcium (Ca) content in the microalga is relatively lower than the other minerals [23]. In addition, some studies revealed that lead (Pb) is totally absent in *Arthrospira* spp. biomass, which is a good indicator for the safe use of *Arthrospira* spp. as a plant growth promoter [24]. However, microalgae are also used in wastewater bioremediation due to their ability to concentrate heavy metals. The mechanisms (extracellular and intracellular) linked with metal absorption are complex, and influenced by microalgal species, metal ion (Pb > nickel (Ni) > cadmium (Cd) > zinc (Zn)) and the growing system conditions (such as pH) [25]. Many studies indicated that microalgae contain some plant growth-promoting substances such as auxins, cytokinins, betaines, amino acids, vitamins and polyamines. Stirk et al. quantified auxin and cytokinin contents in 24 microalgae strains from the *Chlorophyceae*, *Trebouxiophyceae*, *Ulvophyceae*, and *Charophyceae* families. The general trend was that cis-zeatin was the predominant cytokinin. Moreover, microalgae can contain also important quantities of gibberellins and brassinosteroids [7]. Protein hydrolysates are also included among the active ingredients of plant bio-stimulants, and their use in a foliar spray application might enhance the biological activity in crops growth and development. Microalgae contains also amino acids that are a well-known bio-stimulant with positive effects on plant growth and crop yield. Moreover, amino acids can contribute to mitigate the injuries caused by abiotic stresses [26]. In the band of biofertilizers eukaryotic microalgae, anoxygenic phototrophs and cyanobacteria are of prime significance because of their contribution in terms of soil fertility and yield of crops [27]. Biofertilizers are classified by the microorganisms and the benefits achieved by their application: nitrogen-fixators; phosphates- and potassium solubilizing biofertilizers; phosphorus-mobilizing biofertilizers; and biofertilizers for secondary macronutrients, zinc- and iron solubilizers, plant-growth-promoting rhizobacteria (PGPR) (Figure 2), and compost [28]. Biofertilizers are being under extensive research these days as they play a vital role in sustainable agriculture by enhancing the productivity of crops in an efficient and eco-friendly manner thereby reducing the deleterious effects of synthetic fertilizers [29].

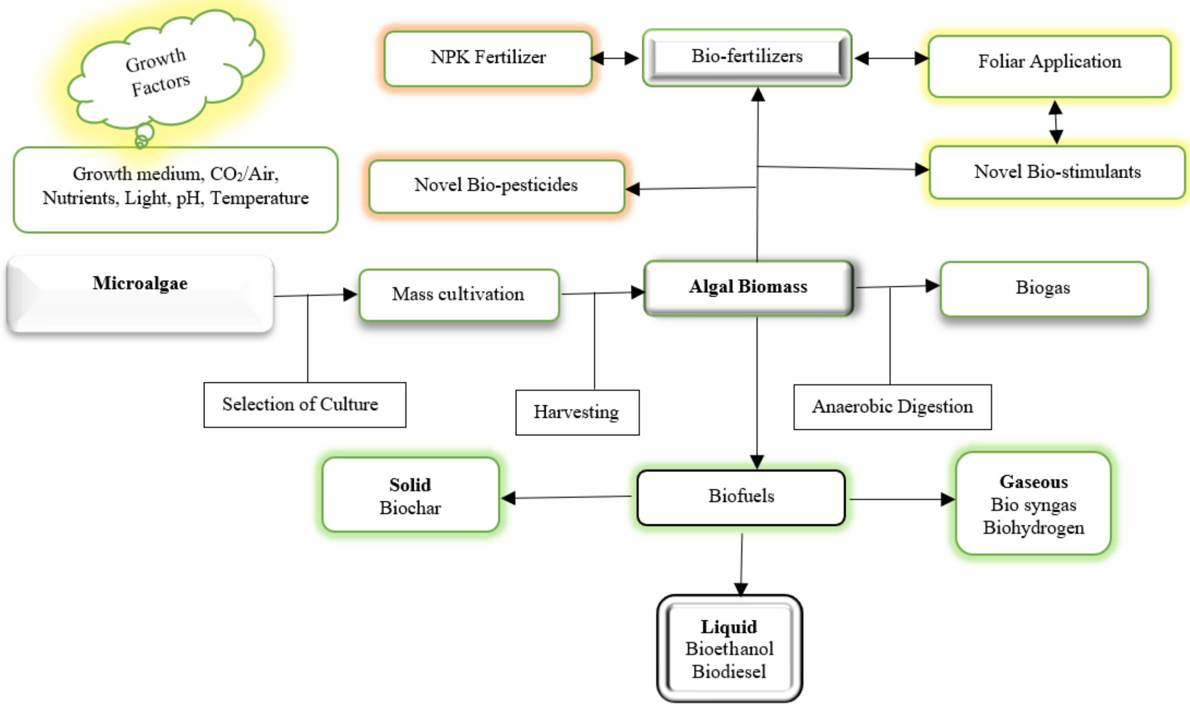

Figure 2. Efficacy of microalgae in sustainable energy and environment

Cyanobacteria and eukaryotic green microalgae have unique performance in the mineralization, mobilization of organic and inorganic, macro and micronutrients, production of bioactive compounds, (polysaccharides, growth hormones, antimicrobial compounds, etc.) can improve the plant growth and thus makes them suitable to be used as biofertilizers [30]. Some salient features of Miroalgae based biofertilizers are elaborated as (i) High yield per unit area can be obtained in a short duration of time and enhance soil fertility [31]. (ii) Energy incentive, renewable and environmentally friendly solutions for modern agriculture [32]. (iii)They are key components in integrated nutrient management (INM) and integrated plant nutrition system (IPNS), leading to sustainable economic development [33]. (iv) They promote antagonism and biological control of Phyto-pathogenic organisms. (v) Application of Nitrogen fixing cyanobacteria is coined as “Algalization” not only enriches soil & plant with N but also helps to overcome the use of chemical N fertilizer [34]. (vi) A lot of microalgae and cyanobacteria are found to excrete extracellular polymeric substances (EPS) into their immediate living environment to form a biofilm. EPS supplements the content of organic carbon in soil, prevents soil erosion and helps to retain proper soil structure [35]. The inoculation of Chlorella spp. alone or in combination with vermiculite increased the stability of soil micro aggregates (0.25–0.050 mm) as compared to chemical fertilizer [36]. (vii) Microalgae also play an important role in the production of growth hormones (cytokinins, jasmonic acid etc.) which can be utilized as bio stimulants in agriculture [37].

Biopesticides are known for their activity against plant pathogens. These compounds, typically presenting antimicrobial, antioxidant, antiviral or antifungal properties, promote crops' development by protecting plants from pathogenic organisms. Plant crops are always at risk due to the existence of pests. Hence, pesticides are used to protect the crops from pests. As the demand of safe and healthy food is increasing, while environment is facing serious problems due to synthetic pesticides; this led to the development of research on biopesticides. Biopesticides are natural or derivatives of living organisms and are biodegradable and environmentally sustainable having less or no negative impact on humans, animals, and environment [38]. According to their origin, they can be classified into biochemical biopesticides {plant growth regulators (PGR) & pheromones}, botanical biopesticides (phenolics & terpenes) and microbial biopesticides(microalgae) [39]. Microalgae are considered as 'living biorefinery' because of their potential to produce a range of green chemicals while converting CO_2 and water to oxygen during photosynthetic process. Microalgae is converted to primary metabolites (carbohydrates, lipids and proteins) and secondary metabolites (terpenes, fatty acids, esters, phenolic compounds, steroids, triglycerides) which can be utilized to produce the biopesticides and biofertilizers which are coined as green chemicals [40]. Microalgae have the capability to mitigate the greenhouse gases generated from thermal plants. During the culture of *Synechococcus nidulans* the intermittent addition of CO2, SO2, NO and ash catalyzed the production of protein enriched biomass and achieved bio-fixing efficiency of 55% for CO2, for assays with injections of 10% CO_2, 60 ppm SO2, 100 ppm NO and 40 ppm ash [41]. Chlorella sp. was used for nutrient removal from crop runoff in wastewater treatment plant; the removal of nitrogen and phosphorus was about 80.5% while the removal of heavy metals varied from 56.5% to 100% [42]. Since the recycling of nutrients favors the sustainable cultivation of Microalgae, therefore Rosa et al. 2015 [43] cultivated *Spirulina sp.* LEB 18 by recycling of culture medium achieved increase in biomass productivity and carbohydrates by 31.4% and 96.5% respectively, found to be potent in the control of pathogens. Chen et al. [44] studied nutrient recycling from liquefaction process for chlorella vulgaris which produced high levels of organic nitrogen and phosphates. Microalgae has the capability to produce phytohormones which are the derivatives of isoprenoids. Phytohormones affects the growth and productivity of microalgae and helps to stabilize various metabolic pathways to produce biomolecules (carbohydrates, proteins and lipids). Hence microalgae culture does not require any synthetic growth catalyst to increase the biomass yield unlike other Agri-systems [45].

IV. Conclusion

The main benefit of microalgae is that their production requires limited non-renewable resources and bears an overall reduced environmental influence. Associated to other photosynthetic organisms, microalgae are hypothetically more appropriate for microbiological improvement, especially for supporting the metabolic reactions. However, the advancement of their applications in agriculture is hindered by various factors. While there is a consensus on the potential benefits of the interaction between microalgae and crops, there is limited scientific evidence underpinning this interaction, compared to other organic/inorganic and microbial fertilizers. The enormous diversity of microscopic algae still remains largely unexplored and little work has been done for the selection and genetic progress of microalgae accession for agriculture.

In the coming years, research efforts should concentrate on finding the relationship between microalgae, plants & environment dealings, to select optimal permutations. Researchers are also going to focus on optimizing application parameters (e.g., rate of application, dose, timing, mode, and plant developmental stage). The quantitative and qualitative characterization of microbial communities as controlled by microalgal species, determining the persistence of effects after microalgal bio-stimulants in foliar application. The impact of climatic (e.g., radiation, and relative humidity) and plant morphological factors (e.g., cuticle thickness and leaf permeability) on the effectiveness of microalgal agricultural products. Finally, the synergistic effects among Microalgae should be at the center of future research aiming to design and develop efficient microalgae-based products with specific bio-stimulation/microbial action.

Microalgae extracts received a greater interest in crop productions as Microalgae Bio-fertilizers (MBF) and Microalgae Bio-stimulants (MBS). Different formulations are now commercially accessible, and a rising number of agrochemical companies are incorporating microalgal extracts into novel MBS and MBF formulations. Microalgal extracts demonstrated several positive benefits, including increased nutrient uptake, induced abiotic stress tolerance, and better crop yield and quality. However, there are still a few questions that need to be answered to better understand how and when microalgal extracts might be employed in crop production to promote agricultural sustainability.

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