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Microalgae-Based Biofertilizers: A Promising Alternative to Chemical Fertilizers

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Abstract- Microalgae have emerged as valuable assets in agriculture, serving as biofertilizers and soil conditioners. In tropical lowland rice cultivation, nitrogen-fixing cyanobacteria-based biofertilizers have proven effective, while eukaryotic, unicellular, green microalgae find application in temperate zones for soil conditioning, particularly in sprinkler-irrigated farmland for erosion control. The potential of microalgae technologies is substantial, yet their success varies due to challenges such as the absence of quality inoculates and a limited understanding of soil microbial ecology. These obstacles hinder the development of integrated management schemes crucial for maximizing the effective exploitation of microalgae in crop production. This review delves into the current state of microalgae applications in agriculture, addressing prospects and challenges across various domains, including crop production, protection, and natural resource management. It emphasizes the need for concerted screening and strain improvement programs, coupled with advancements in product formulation technologies, to overcome existing limitations. Furthermore, the review provides an overview of recent advances, novel technologies, their commercialization status, and outlines future directions. By shedding light on the potential and hurdles, this comprehensive analysis aims to guide efforts towards realizing the full spectrum of benefits that microalgae can offer in enhancing agricultural practices.

Key words: Microalgae, Biofertilizer, soil fertility, crop production, biostimulant.

I. INTRODUCTION

Global ecological deterioration brought on by the misuse of synthetic agrochemicals has resulted in eutrophication, ocean dead zones, soil infertility, and a loss of biodiversity (Köhler and Triebskorn 2013; Chagnon et al. 2014; Hallmann et al. 2014; van der Sluijs et al. 2014). One potential answer is the use of microalgae as biofertilizers.Since biofertilizers not only increase agricultural output but also reduce pollution in the environment, they are seen as a sustainable, economical, and ecologically friendly substitute for synthetic fertilizers (Kawalekar S.J. 2013). According to Abdel-Raouf et al. (2012), biofertilizers are products that contain natural compounds or living microbes generated from creatures like bacteria, fungi, and algae. These compounds improve the chemical and biological properties of soil, promote plant growth, and restore soil fertility.

Eukaryotic green and prokaryotic blue algae are examples of the common photosynthetic organisms known as microalgae.They offer enormous potential for utilisation as biological resources in a variety of industries, including fuel, feed, health goods, and medicine. Because of their capacity to improve the utilisation of macro and micronutrients and enrich soil nutrients, these intriguing creatures can also be employed in contemporary agriculture. Microalgae can create plant growth hormones, polysaccharides, antibacterial compounds, and other metabolites to promote plant growth in addition to enhancing the fertility and quality of the soil (Kumar, 2018, p. 377). According to the pigments they contain, algae are divided into three groups: green, brown, and red. According to reports, several types of algae have positive impacts on a few vegetable crops (Abdel-Mawgoud et al., 2010). They are naturally occurring bioactive substances that are high in microelements (Co, B, Mo, Zn, and Cu), minerals, protein, lipids, carbs, and vitamins. Apart from releasing trace elements that are bound to the soil (Chapman and

Chapman, 1980), seaweed fertilizer a unique combination of N, P, K, trace elements, and dissolved simple sugar that is safe for humans, animals, and the environment (Sathya et al., 2010).According to the chemical analysis of Spirulina platensis used in this study, its protein content was 58.2% of its dry weight, its carbohydrates made up 23.2–24.5%, and its essential minerals ranged from 2.7–3% and could reach 7% of its dry weight. Spirulina platensis is a rich source of potassium and contains significant amounts of Ca, Cu, Fe, Mg, Mn, P, and Zn (Marrez et al., 2014).A varied collection of photosynthetic organisms, microalgae have shown a wide range of applications in many industries. Their potential in agriculture, especially as biostimulants, has been underestimated in comparison to macroalgae, despite their widespread exploration in biofuels, aquaculture, and bioremediation. Because they can fix nitrogen, cyanobacteria have long been used as biofertilizers and biocontrol agents against plant diseases.

A shift to a bio-based economy is widely accepted, acknowledging the necessity for increased food production on a worldwide scale in the face of climatic problems. It is widely recognized that blue-green algae (BGA) improve rice yields and the nitrogen economy of paddy fields. The mere presence of BGA in the soil leads to the formation of soil aggregates, which enhance the soil's chemical and physical properties with respect to the crop's physical surroundings, minimize soil loss during the rainy season, and regulate temperature and aeration.BGA contributes to the replenishment of soil nutrients by releasing exopolysaccharides and bioactive substances.(Chatterjee, A., Rai, R., Yadav, S., Singh, S., Agrawal, C., &Rai, L. C. (2017)).It is critically necessary to find a renewable substitute for synthetic chemical fertilizers in the context of agricultural sustainability. The creation of contemporary crop cultivars whose yield is extremely responsive to intensive fertilization, along with increased use of synthetic chemical fertilizers, have enhanced crop productivity globally (Khush, 2001, p. 815).

For instance, a significant amount of phosphorus (P), a macronutrient that is vital for plants, is probably present in soils as forms that are either unavailable or inaccessible to crops. This makes P fertiliser even more crucial. However, the depletion of the deposits is a serious worry because rock phosphate, the basic material for P fertilizers, is a limited resource that is unevenly distributed in a few parts of the world (Desmidt et al., 2014, p. 336).Furthermore, burning fossil fuels to fix atmospheric N2 is necessary for the production of nitrogen (N) fertilizers, and extensive use of N fertilizers enriches reactive N compounds, which causes air pollution, soil acidification, and water eutrophication (Hayashi et al., 2021, p. 117559). Therefore, the implementation of eco-friendly soil fertilization techniques and renewable alternatives to chemical fertilisers (Lin et al., 2019) as well as methods to improve crop nutrient use efficiency (Ochiai, Oba, Oda, Miyamoto, &Matoh, 2022) should be investigated in order to create a sustainable agricultural system globally. Microalgae have several uses. They can produce biomass that can be used for fertilisers, food, fuel, and animal feed (Metting 1990).

According to Brennan and Owende (2010), microalgae have the potential to significantly impact vital ecosystem services because they can (i) be grown in wastewater and agricultural runoff, recovering excess nutrients and reclaiming water for future use, and (ii) sequester carbon dioxide and nitrous oxides from industrial sources, lowering greenhouse gas emissions. However, a number of obstacles need to be removed before microalgae production may be considered economically feasible, particularly for the production of biofuels (Brennan and Owende 2010; Mata et al. 2010; Wijffels and Barbosa 2010; Borowitzka 2013; Pragya et al. 2013). This section focuses on how using green algae and cyanobacteria as biofertilizers can enhance soil fertility and quality while encouraging plant development.There is also discussion of recent scientific advancements and the potential for their use in contemporary agriculture.

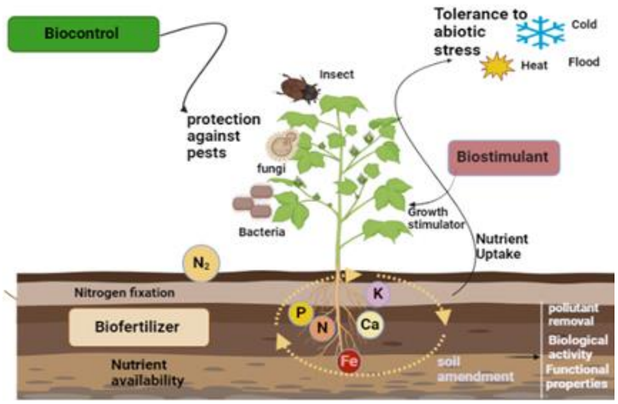

Figure 1 shows how using cyanobacteria and green algae as biofertilizers can enhance soil fertility and quality while encouraging plant development.

II. GEOGRAPHICAL DISTRIBUTION OF PUBLICATIONS

Over the last four years, there has been a significant growth in research on the application of microalgae in agriculture; in 2023, there were more studies than in 2020 (Figure 2). This exemplifies how microalgae are used in agriculture, which may become one of the most important applications of microalgae technology in the years to come. With almost half of the studies published between 2001 and 2022, Asia has been at the forefront of this field's study, with India leading the way with 87 papers. In the last decade, India has emerged as a major agricultural exporter, possessing the world's greatest net cultivated area (USGS, 2021).However, the Indian agriculture sector has been beset by a number of problems, such as low farm yields, limited water supplies, and environmental and soil degradation (Chew and Soccio, 2016; Narain, 2020). These problems may be the primary drivers behind a thorough investigation into environmentally friendly solutions. With 18 publications, Spain has been the most prolific country in Europe. Italy comes in second with 17. In Africa and America, Egypt and Brazil stood out with 33 and 26 published studies, respectively. Germany and France own 51% of the EU's total exploited agricultural area and 49% of its arable land, despite Spain and Italy having significant contributions to the European agricultural sector. Furthermore, by employing 20% fewer pesticides between 2011 and 2018 in favour of more ecologically friendly substitutes like crop rotation and precision farming technologies, Italy emerged as the most sustainable agricultural industry in Europe (Eurostat, 2020).

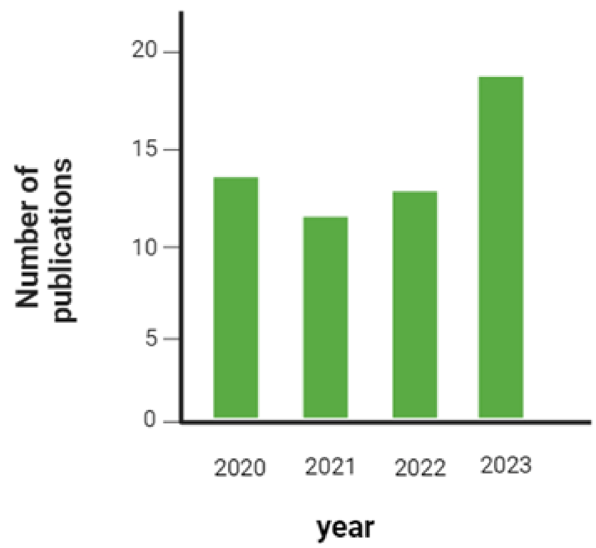

Figure. 2 shows the global evolution of publications about the use of microalgae in agriculture.

Microalgae and cyanobacteria distribution in agricultural publications

Utilising dry biomass from Chlorella minutissima reduced the leaching of nitrate from farmland and increased leaf N content of spinach (Spinaciaoleracea) plants (Sharma et al., 2022). The application of Asterarcys quadricellulare extracts significantly stimulated N assimilation and the nitrate reductase activity of potato(Solanum uberosum) plants (Cordeiroetal.,2022).The applications of C.vulgaris biomass and chemical fertilizer resulted incomparable levels of shoot N uptake in wheat (Triticum aestivum) plants (Schreiber et al., 2018). These results demonstrate the effectiveness of the microalga-based fertilizer. However, the level of shoot P uptake was lower in the wheat plants grown under the microalgal treatment than in those grown under the chemical fertilizer treatment (Schreiber etal., 2018), suggesting that microalgal biomass acts as a slow-release P fertilizer. Microalgae can store as polyphosphates (DelgadilloMirquezetal.,2016;Solovchenkoetal.,2019; Chuetal.,2021),which are degraded slowly by soil microbes (Powell et al., 2011; Ray et al., 2013; Solovchenko et al., 2019). Furthermore, hydrothermal carbonization of microalgal biomass enhances its characteri-stics as a slow-release fertilizer, which increases the amount of moderately available P in soils more persistently compared with chemical fertilizer (Chu et al., 2021) .Such fertilizer characteristics might increase the nutrient use efficiency of crops and/or reduce environmental pollution by suppressing the leaching of nutrients from farmland (Coppens et al., 2016; Jimenez et al., 2020; Sharma et al., 2022).The application of microalgal extracts enriches essential macronutrients such as P, potassium, calcium, and magnesium in tomato plants (Suchithra et al., 2022) . Microalga-based fertilizers also supply essential micronutrients as well as beneficial elements for plants (de Haes et al., 2012; Maurya et al., 2016; Wuang et al., 2016; Silva et al., 2019). In a wheat cultivation test, the application of microalgal biomass increased the contents of zinc, iron, copper, and manganese in plants (Rana et al., 2012; Prasanna et al., 2013; Renuka et al., 2017). Microalgal biomass rich in selenium, a beneficial element for plants, has been also suggested to serve as an effective fertilizer (Han, Mao, Wei, Shang, & Zhou, 2020, p.p.2071).

Production of Biofertilizers: The Algal Industry

The commercial production of biofertilizers considers several aspects as the microorganism's growth and nutrient profile, the assembly of the microbes, suitable conditions of maintaining an active biomass and formulation of the inoculum

Table 1: Production of biofertilizer as commercial level

s.no.	StepsinCommercialProductionofBiofertilizer
1	Exploration and identification of active microbial consortia
2	Isolation of select active organisms
3	Rapid screening and selection of beneficial target microbes
4	Efficacyofmicrobialtargetpopulation
5	Selection of carrier substance as well as the methods
6	Choosing the propagation technique
7	Investigations on nutrient studies and design of prototype and testing
8	Field trial sandlarge-scaletesting

Synthesis of biostimulant and fertilisers based on microalgae

Since microalgae have a better photosynthetic efficiency and a larger unit dry matter per yield/land area than land plants, they have been viewed as a possible industrial source of food, chemicals, and bioproducts (Chen et al., 2022).

Their capacity to adapt to a wide range of environmental conditions and adopt various modes of nutrition, including autotrophic (fully photosynthetic), mixotrophic (able to use both reduced organic carbon and light sources), and heterotrophic (fermentative approach with utilisation of organic carbon source), accounts for the presence of a multitude of chemical compounds (Udayan et al., 2022).

The main component and functional material for the manufacturing of biostimulants or biofertilizers is microalgae biomass. Mass production of agrochemicals and biofertilizers depends heavily on the systematic assessment of biomass production techniques and an understanding of their appropriateness. In open raceway ponds (ORP) or closed PBRs, microalgae are often mass-cultivated using the phototrophic method of nutrition, which uses carbon dioxide, sun energy, and inorganic minerals.

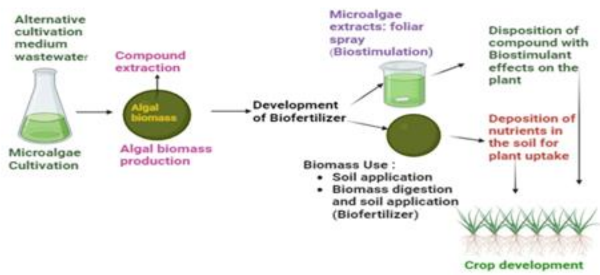

Figure 3: Three main steps are involved in the production of microalgae biomass or its derivatives: (i) cultivation, (ii) harvesting, and (iii) downstream processing, which includes dewatering, extraction, and purification or formulation. The production tactics differ with respect to intended purpose such as for food, feed, fuel or farm applications.

III. CRITICAL EXAMINATION OF MICROALGAL BIO STIMULANTS FOR SUSTAINABLE AGRICULTURE PRACTICES IN RELATION TO ALGAE

Microalgae are a diverse collection of mostly single-celled photosynthetic organisms that synthesise a variety of compounds using CO2 and sunshine. The applications of microalgae in biofuels, aquaculture and animal feed, trash bioremediation, nutraceuticals, medicines, and cosmeceuticals have all been investigated thus far (Chanda, Merghoub, & EL Arroussi, 2019). Compared to macroalgae, microalgae have received less attention in the context of agricultural uses. In rice fields, cyanobacteria, or blue-green algae, have historically been recognised for their ability to fix nitrogen (~20–30 kg N/ha) and are advantageous for a number of different crops (Chakdar et al., 2012). As a slow-releasing biofertilizer and soil conditioner, collected microalgal biomass has been applied to the soil (Dasgan et al., 2012; Garcia-Gonz and Sommerfeld, 2016).

In contrast, the use of living cyanobacteria is recognised to function as a possible biocontrol agent against plant diseases by activating plant defence enzymes and producing hydrolytic enzymes and antibacterial chemicals (Gupta et al., 2013).Improved crop quality and quantity are necessary to enable global food security and support the expanding human population in the face of current climate change. The current consensus is that we must build a sustainable circular economy and biorefinery approaches in order to shift from a petroleum-based to a bio-based economy. Long regarded as a rich source of plant biostimulants, both macroalgae (seaweeds) and microalgae present an alluring economic prospect in agronomy and agro-industries.

The use of macroalgae biostimulants has been thoroughly investigated thus far. On the other hand, although microalgal biostimulants are known to improve crop development, growth, and yields, their commercial application is limited by a lack of research and production costs.The present investigation centers on the existing understanding of significant sources, potential biostimulatory compounds, and quantitative data obtained from algae (Kapoore, Wood, & Llewellyn, 2021, p. 107754). We provide an overview of the potential of microalgal biostimulants to enhance agricultural productivity and quality in particular. The viability and potential of co-cultures, the distinct biostimulant effects generated by microalgae extracts, and the subsequent co-application with other biostimulants/biofertilizers are highlighted as important variables.

Additionally covered are the market's current status, recent advancements and successes in the field of extraction techniques, application kind, application timing, and regulatory considerations.

The other aspects of the circular economy and biorefinery approaches that are discussed include the integration of waste resources and the use of high throughput phenotyping and -omics tools in isolating novel strains, examining synergistic interactions, and shedding light on the underlying mode of microalgal biostimulant action.

IV. MICROALGAE AS VERSATILE POSSIBILITIES IN CONTEMPORARY

AGRICULTURE :PRESENT DEVELOPMENTS, OPPORTUNITIES, AND DIFFICULTIES

Algae are amazing photosynthetic organisms that are extensively distributed in nature. These species include green algae and cyanobacteria. They are extremely promising for a number of industries ,including animal feed, nutraceuticals, biofuels, and pharmaceuticals. Algae are becoming more widely acknowledged for their advantageous functions in the field of contemporary agriculture. They enhancethe availability of nutrients, support soil fertility and organic matter, and encourage soil microbial activity (Renuka et al., 2018).With the goal of increasing crop output in a way that is both economical and environmentally benign while reducing the environmental impact of synthetic fertilizers, biofertilizers have become essential to sustainable agriculture (Singh et al., 2011a, Singh et al., 2011b).Blends of biofertilizers based on photosynthetic organisms, such cyanobacteria and microalgae, are becoming more and more popular. These organisms are essential for maintaining the fertility of the soil an used increasing agricultural production(Lietal.,2017).Some cyanobacteria are very good at fixing nitrogen through mechanisms such as biological nitrogen fixation. Growth hormones and other antimicrobial chemicals, which are essential for plant health and foster an environment that is favorable for soil microbes, are produced by both cyanobacteria and green algae.

In the modern method, the synergistic application of cyanobacteria in combination with microalgae, bacteria, fungi, or their biofilms is investigated. By working together, they can be used in more areas, which increase their usefulness in agricultural techniques. This demonstrates how algae, with their wide range of uses, are becoming essential to productive and sustainable farming methods. Renuka (2018)&Guldhe(2018).The promise of biotechnology in preserving soil fertility and health through the use of cyanobacteria and microalgae. The unsung heroes of the soil, cyanobacteria and microalgae, are frequently disregarded in the busy realm of soil micro biota but have enormous potential for preserving the delicate nutrient balance and enhancing soil health. Although numerous researches have focused on bacteria and fungi that love plants, the vital contributions played by these microscopic photosynthetic creatures have received less attention. This is true even though their pervasive presence in soil may be able to address some of the problems caused by the careless use of agricultural pesticides, which can result in problems including unstable soil structure and the buildup of harmful contaminants.

In a comprehensive analysis by Sudharsanam Abinandan and colleagues (2019), the emphasis shifts to microalgae and cyanobacteria, exposing their hidden abilities. The review emphasizes their noteworthy contributions to crop productivity and explores their potential applications. By fostering plant growth, establishing connections with fellow microbes, and even detoxifying harmful chemical agents through collaborative efforts, these microorganisms showcase their ecological prowess. Key highlight of the review is the exploration of advanced biotechnological methods, such as recombinant technology with genomic integration. These methodologies open new avenues for developing desirable traits in microalgae and cyanobacteria, paving the way for their meaningful application in sustainable agriculture. The review provides a balanced discussion on the strengths and limitations of these advanced techniques, offering insights into their role in enhancing soil fertility and overall health. In essence, the review aims to draw attention to the underestimated heroes beneath our feet and encourages a reevaluation of their potential impact on sustainable agriculture, all with the hope of a healthier, more balanced ecological (Abinandan, Subashchandrabose, Venkateswarlu, &Megharaj, 2019, p. 981).

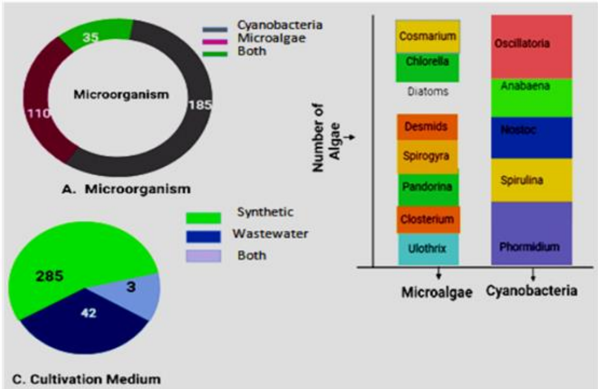

Figure. 4 Distribution in agriculture application studies by (A) type of microorganism; (B) number and genus of the microalgae and cyanobacteria used in the studies; (C) cultivation medium used to grow the biomass.

V. AN EXTENSIVE REVIEW OF ENVIRONMENTALLY BENEFICIAL BIOFERTILIZERS MADE FROM LIVE THINGS

Biofertilization is an environmentally friendly practice used in sustainable agriculture. Biofertilizers increase plant productivity by enhancing the nutritional content and fertility of the soil. Because of their natural degradation, a large variety of living organisms can be used as biofertilizers to improve soil fertility without posing a pollution risk. Microorganisms such as bacteria micro fungal and microalgae or macro organisms such as higher plants, macro fungi, and macroalgae may be considered among these organisms. The use of biofertilizers—derived from living organisms or their waste products—is expected to increase instead of chemical fertilizers, which build up heavy metals in soil. By preserving soil, the use of biofertilizers in agriculture strives for sustainable development. This will lessen the effects of climate change and its consequences and several major pollution-related diseases such as cancer, liver and renal failure, and immunological disease (Ammar, E. E., Rady, H. A., Khattab, et.al.,(2023).

Role of blue-green algae in nitrogen economy of Indian agriculture

In the sphere of agriculture, microalgae are essential and multifaceted, providing creative solutions and supporting sustainable farming methods. Their potential advantages in different areas of agricultural systems are highlighted by a number of research (Köhler and Triebskorn, 2013; Chagnon et al., 2014; Hallmann et al., 2014; van der Sluijs et al., 2014).

Biofertilization

Microalgae are efficient biofertilizers that add vital nutrients to soil. They are important members of agricultural ecosystems because of their capacity to fix nitrogen and create substances that improve soil fertility (Kawalekar, 2013). By lowering environmental pollution and encouraging sustainable farming, biofertilizers made from microalgae offer a natural and environmentally beneficial substitute for synthetic fertilisers.

- **Soil Conditioning**
- Eukaryotic green microalgae, when applied as soil-conditioning agents, aid in erosion control, particularly in temperate zones with sprinkler-irrigated farmland. Their role extends beyond nutrient enrichment, as they contribute to improving soil structure and functionality. Consequently, this promotes improved plant development and improves the soil's general health.

- **Nutrient Recycling**
- Microalgae can thrive on waste effluents that are high in nutrients. According to Abdel-Raouf et al. (2012), they offer a way to recycle extra nutrients for plant growth by absorbing them. Microalgae provide a more sustainable method of managing nutrients in agriculture because of their slow-release nature, which contrasts with chemical fertilisers' fast release.

- **Biological Resource for Agriculture**
- In agriculture, microalgae are regarded as important biological resources. In addition to enriching soil, microalgae in modern agriculture also produce plant growth hormones, polysaccharides, antimicrobial compounds, and

other metabolites that support overall plant health and growth. These applications span five different fields, including medicine, health products, feed, and fuel.

- **Diversity and Adaptability**
- There are several types of microalgae, such as bacterial blue algae and eukaryotic green algae. This variety makes it possible to adjust to various farming conditions and production techniques. Different strains of microalgae are being investigated by researchers in an effort to maximise their effectiveness in diverse crops and agro-ecosystems.

- **Reduction of Chemical Fertilizers**
- The use of microalgae in agriculture offers a sustainable approach to reduce reliance on chemical fertilizers. This is particularly significant in addressing issues such as rising fertilizer prices, groundwater pollution, and concerns related to human health (Gawish et al., 2012). Microalgae-based solutions present a promising avenue to minimize the environmental impact of conventional agricultural practices.Their versatile applications contribute to the development of sustainable and environmentally friendly practices in modern farming, addressing challenges posed by the overuse of synthetic agrochemicals. Ongoing research and advancements in microalgae technology hold the potential to further revolutionize the agricultural landscape.

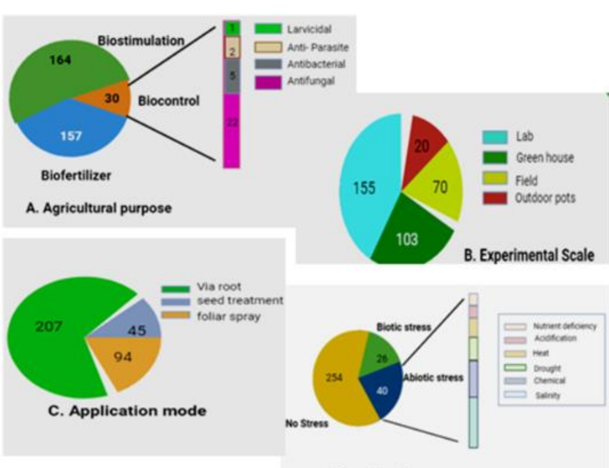

Figure 5 illustrates the role of microalgae in agriculture, which includes nutrient recycling, soil conditioning, biofertilization, and the provision of a rich source of biological resources. The purpose of the biofertilizer, the experimental size, the various application modes, and the growth circumstances (A, B, C, D).

VI. CONCLUSIONS

Microalgae are a broad collection of photosynthetic organisms that have shown a wide range of applications in different industries. Compared to macroalgae, their potential in agriculture, especially as biostimulants, has been underestimated, despite their widespread exploration in biofuels, aquaculture, and bioremediation. Because they can fix nitrogen, cyanobacteria have historically been used as biofertilizers and biocontrol agents to combat plant diseases. Everyone agrees that a shift to a bio-based economy is necessary, given the need for increased food output worldwide in the face of climate change.

The biostimulant qualities of macroalgae have been thoroughly investigated, while microalgal biostimulants, although beneficial for crop development, encounter challenges in commercialization because of low research and production costs. A thorough review of the potential of microalgal biostimulants to improve crop quality and productivity can be found in Kapoore et al. (2021).

It explores the potential synergies with other agricultural inputs, the viability of co-cultures, and the impacts of certain biostimulants. The analysis includes regulatory issues, timing, extraction and application methods, and the state of the market. The circular economy and biorefinery approaches are also examined, with a focus on waste resource integration and sophisticated instruments for strain isolation and comprehension of microalgal biostimulant action.

In summary, the study offers insightful information about the state of knowledge, issues, and new developments surrounding microalgal biostimulants. By tackling important issues and possible roadblocks, it paves the way for maximizing microalgae's potential to support resilient and sustainable agriculture.

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