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Cyanobacteria and microalgae as eco-friendly and multi-functional options for modern agricultural technologies

A Graduation Research Project Submitted to the Department Biology in Partial Fulfillment of the Requirements for the Completion of the Degree of Bachelor of Science in Biology

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This Research Project has been Approved and Accepted in Part by Fulfilling the Requirement to Obtain a Bachelor's Degree in Biology

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بسم الله الرحمن الرحيم

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Abstract

The use of cyanobacteria and microalgae has recently increased due to their benefits and capabilities, as they can improve soil fertility and agricultural productivity to meet the global food demand. Wide range of metabolites are produced by cyanobacteria and microalgae such as polysaccharides, hormones and other substances that improve plants growth and crop yield and thus they are considered as excellent biofertilizer and soil conditioner. They also have an important role as biostimulant by enhancing the plants quality through improving nutrient use efficiency and tolerance to abiotic stress.

Cyanobacteria can also fix nitrogen and improve soil and plant nitrogen status and thus decrease the use of chemical fertilizer. Moreover, microalgae and cyanobacteria can efficiently fix carbon, and both can uptake phosphate and make it available for the plants' use. Also, they contribute to the formation of biological soil crust in which they can form a layer that protects against soils' erosion and desiccation. Cyanobacteria and microalgae also contribute to the production of antimicrobial compounds that exhibit antagonistic effects against pathogenic microorganisms, suppressing them by different mechanisms that in turn protect plants from diseases and maintaining them in healthy state.

In this review, we will focus on the benefits of using cyanobacteria and microalgae in the agricultural sector and their roles in enhancing soil health, and fertility. Which leads to improving plant growth and increasing crop yield to meet the increasing food demands. In addition to their important role in reducing soil damage and protecting the environment.

الخلاصة

فى الآونة الاخيرة زاد استخدام السيانوبكتريا (الطحالب الخضراء المزرقة) والطحالب الدقيقة نتيجة لفوائدهم وقدراتهم المتعددة، حيث يمكنهما تحسين خصوبة التربة والإنتاج الغذائي لتلبية الطلب المتزايد للغذاء. مجموعة متنوعة من المواد الايضية يتم انتاجها بواسطة السيانوبكتريا والطحالب الدقيقة مثل السكريات والهرمونات ومواد أخرى تحسن نمو النباتات وإنتاجية المحاصيل ولذلك تعتبر بمثابه اسمدة حيوية ومحسنات قوية للتربة و أيضا لديها دور مهم كمنشطات و محفزات حيوية للنبات، حيث انها تحسن جودة النبات عن طريق تحسين كفاءة استخدام المواد الغذائية وزيادة التحمل للإجهاد الغير حيوي.

تستطيع السيانوبكتريا تثبيت النيتروجين وزيادته فى التربة وبالتالي سيؤدى ذلك الى تقليل استخدام الأسمدة الكيمائية و المعدنية. أيضا تستطيع هذه الكائنات الدقيقة تثبيت الكربون وكلاهما يستطيعان تيسير الفوسفات في التربة وتحويله لشكل متاح تستطيع النباتات امتصاصه. أيضا كلاهما يساهمان في تكوين قشرة التربة البيولوجية حيث ينتج عن ذلك تكوين طبقة تحمي ضد الجفاف والتآكل . تساهم كلا من السيانوبكتريا والطحالب الدقيقة في انتاج مضادات ميكروبية تنتج تأثيرات مضادة التي تثبط النمو الميكروبي الممرض وتساعد على قمعهم بعدة آليات مختلفة مما يحمي النباتات من الامراض ويحافظ عليهم بحالة صحية جيدة.

في هذا البحث المرجعي سنسلط الضوء على فوائد استخدام السيانوبكتريا والطحالب الدقيقة في المجال الزراعي ودورهم في تحسين التربة وصحتها وخصوبتها. مما ينتج عنه تحسين نمو النباتات و زيادة انتاج المحاصيل الغذائية وتلبية الطلب المتزايد للغذاء ، أيضا لا ننسى دورها المهم في تقليل الاضرار على البيئة وحمايتها.

List of Abbreviations

Anabaena laxa (A. laxa)

Anabaena oryzae (*A. oryzae)*

Anabaena variabilis (A. variabilis)

Ammonia or ammonium (NH_4^+)

Antimicrobial resistance (AMR)

α-linolenic acid (ALA)

Arsenic (As)

Cadmium (Cd)

Carbon (C)

Coagulase-negative *Sthaphylococcus* (CoNS)

Coimbra Collection of Algae (ACOI)

Dissolved Organic Carbon (DOC).

Docosa-pentaenoic acid (DPA)

Dry weight (DW)

Eicosapentaenoic acid (EPA)

Erysiphe betae (E. betae)

Extracellular polymeric substances (EPS)

Hexadecatrienoic acid (HTA)

Lead (Pb)

Mercury (Cr)

Mercury (Hg)

Nitrogen(N_2)

Carbon Dioxide (Co_2)

Biological nitrogen fixation (BNF)

World Meteorological Organization (WMO)

Photobioreactors (PBRs)

Nostoc muscorum (N. muscorum)

Phosphorus (P)

Phosphorus Solubilizing Microorganisms (PSM)

Plant biostimulants (PBs)

Polychlorinated Biphenylsn (PCBs)

Reactive oxygen species (ROS)

Refining photobioreactors (PBRs)

Remazol Splendid Blue R color (RBBR)

Spirulina platensis *(S. platensis)*

Superoxide Dismutase (SOD)

Temperature(T)

Cellicius (C)

The Blue Biotechnology and Ecotoxicology Culture Collection (LEGE-CC)

Total Carbon (TC)

U.S Environmental Protection Agency (EPA)

List of symbols

Liter per micromole (L/umol)

Parts per million (ppm)

Chapter(I)
Introduction

Introduction

Cyanobacteria are historically known as blue green microalgae, they are ancient prokaryotic microorganisms, autotrophic, Gram negative that are capable of photosynthesis. These microorganisms have a variety of photosynthetic pigments such as chlorophyll and carotenoids, phycocyanin and phycoerythrin. They found in different environments including oceans and soils may found as individual or as colonies (crust or blooms). In other hand microalgae are microscopic photosynthetic algae, but unlike cyanobacteria they are eukaryotes.

The cyanobacteria exhibit a wide range of morphological variation ,they can be classified as unicellular, branching filamentous, or heterocyst for nitrogen fixation (Kalyanasundaram *et al.,* 2020), cyanobacteria and microalgae vary in shape and size, they create an extensive range of compounds that find applications in the feed, food, nutritional, and pharmaceutical industries as they can grow in a variety of environmental circumstances (Mandal and Mallick, 2014).

In fact, there are two common classifications of algae: macroalgae and microalgae. Macroalgae, known as large algae, that are sometimes known as "seaweeds", which normally live in freshwater and marine habitats (Ge *et al.,* 2018; Lawton *et al.,* 2013). In other hand small algae known as "microalgae" are mostly present in aquatic, subaerial surfaces, and terrestrial environments, including all kinds of soil. They constitute the component of phytoplankton (Olaizola, 2003; Tomaselli, 2004; Sarwer *et al.,* 2022).

In nature, microalgae and cyanobacteria are well known as the main microbial beneficial photosynthetic agents as they have roles in agriculture and can enhance the chemical and biological characteristics of the soil, promote plant development, and soil fertility, as crop production becomes increasingly important in order to meet food demand expectations while minimizing environmental damage. Numerous studies have shown a correlation between the use of microalgae biofertilizers and increased crop yields, biomass accumulation, and nutrient uptake (Kalyanasundaram *et al.,* 2020).

Utilizing cyanobacteria as a biofertilizer raises the amount of organic matter in the soil and aids in the biological fixation of nitrogen (Prasanna *et al*., 2015; Bidyarani *et al*., 2016; Rana *et al*., 2012; Ramakrishnan *et al*., 2023). Field studies indicated that cyanobacteria increased the plant's root and shoot length, fresh and dry weight, micronutrient uptake, grain weight and yield, also they can be applied in saline soil to increase plant tolerance ability to hyper saline conditions.

Microalgae also play an important role in agriculture through the generation of organic acids for phosphorus solubilization. They have a great impact in increasing levels of soil organic matter besides the creation and releasing of bioactive compounds such vitamins, antioxidants, and plant growth regulators. Their role in bioremediation of wastewaters and breakdown of emerging pollutants by specific pathways has gained much attention in recent decades. Also, their role as biofertilizer in which can increase plant development and strength. Additionally, they are also considered as plant biostimulants that enhance the response to abiotic stress and the growth of plants (Chanda *et al.,* 2019; Hamed *et al.,* 2022b).

Agriculture has recently seen a rise in the usage of cyanobacteria and microalgae for the biocontrol of plant diseases (Kumar *et al*., 2016). According to Kulik, (1995) cyanobacterial extract showed bioactivity against a variety of plant pathogens e.g., *Botrytis cinerea* in strawberries, *Erysiphe polygoni* (powdery mildew) in turnips, and damping-off in tomatoes.

Today, the use of cyanobacteria and microalgae in agriculture has been well documented to have many benefits to soil and was reported to have advantages on the environment as many studies are still on progress but their results show positive effects.

Therefore, the main objective of this review is to highlight the positive role of cyanobacteria and microalgae in improving soil health, increasing plant growth and productivity, preserving soil from salinity, desertification, and degradation of agrochemicals and emerging contaminants. Which may have a good future economic and environmental impacts.

Aims of work

The purpose of this review study is to outline:

- Role of microalgae and cyanobacteria in nitrogen fixation and biofertilization
- Role of microalgae and cyanobacteria in CO_2 fixation
- Role of microalgae and cyanobacteria in formation of biological soil crusts
- Uptake of phosphate (Phosphate solubilization)
- Role of microalgae and cyanobacteria as plant biostimulants
- Degradation of agrochemicals
- Importance of cyanobacteria and microalgae in reclamation of salt affected soils
- Cyanobacteria and microalgae as biocontrol agents (Biofungicide, Bio bactericide Biopesticide)
- Microalgal and cyanobacteria forms in improving grain yield and yield components
- Role of microalgae and cyanobacteria in heavy metal removal

Chapter (II)
Literature Review

2.1. Nitrogen Biofertilizers

Nitrogen limits plant growth, thus for plants to flourish, the amount of nitrogen in the soil must be sufficient and available for plants. Biofertilizers aid in maintaining the soil's nitrogen levels by providing this nitrogen (Rana *et al.*, 2019). The best use of nitrogen biofertilizer depends on the kind of crop that has been planted because different biofertilizers differentially work in different types of soils (Raja, 2013). The nitrogen bio-fertilizers that are employed as bioinoculants may have a symbiotic or nonsymbiotic relationship with the plant (Stancheva *et al.*, 2013). Among myriads of nitrogen biofertilizers, *Rhizobia* spp. are used for legume crops, while *Azolla* is used for grassland rice paddies, *Acetobacter* spp. are used for sugarcane, and *Azospirillum*/*Azotobacter* spp. are used for nonlegume crops (Ghumare *et al.*, 2014).

2.1.1. Nitrogen Fixation by Cyanobacteria

Cyanobacteria, formerly known as blue-green algae, are photosynthetic microscopic organisms. They are considered as one of the significant sources of high-yield nitrogen fixers. Biological nitrogen fixation (BNF) is the process by the nitrogenase enzyme catalyzes the conversion of inert dinitrogen (N_2) to a combined form (Kulasooriya and Magana-Arachchi, 2016). These N_2-fixing prokaryotes can be either autotrophic or heterotrophic, aerobic, or anaerobic. Since they don't compete with crop plants and heterotrophic soil microflora for carbon and energy. The free-living, photosynthetic cyanobacteria convert atmospheric N_2 to organic nitrogen that is used by higher plants, or just by crop plants (Lau *et al.*, 2015).

Cyanobacteria use a specific absorption method to passively diffuse ammonia or ammonium (NH_4^+) from the soil. A particular high-molecular metalloprotein enzyme called nitrogenase is responsible for N_2 fixation; in the presence of hydrogen, it converts molecular nitrogen to ammonia (Himani *et al.,* 2015). Under 40 ppm concentration, cyanobacteria can convert atmospheric N_2 to ammoniacal N. However, more than 70 ppm is harmful to the cell metabolic system (Kaushik, 2009). Heterocyst is a thick-walled modified cell, which is considered as a specialized site for N_2 fixation by the nitrogenase enzyme. *Aulosira*, *Anabaena*, *Nostoc*, are heterocystous species (Fig. 1) however, *Oscillatoria*, *Gloeothece*, and *Gloeocapsa* are non-heterocystous cyanobacterial species.

The nitrogenase enzyme activity of heterocystous and filamentous cyanobacteria in the orders *Nostocales* and *Stigonematales* is often light-dependent, making them promising candidates for use as biofertilizers. In fact, differences exist between heterocystous and non-heterocystous cyanobacteria and between symbiotic and nonsymbiotic N_2-fixing bacteria in terms of their N_2 fixation process (Adams *et al.*, 2006). Fig. 2 represents variable types of free-living and associative molecular N_2 fixing species with representative examples for each (Rai, 2019).

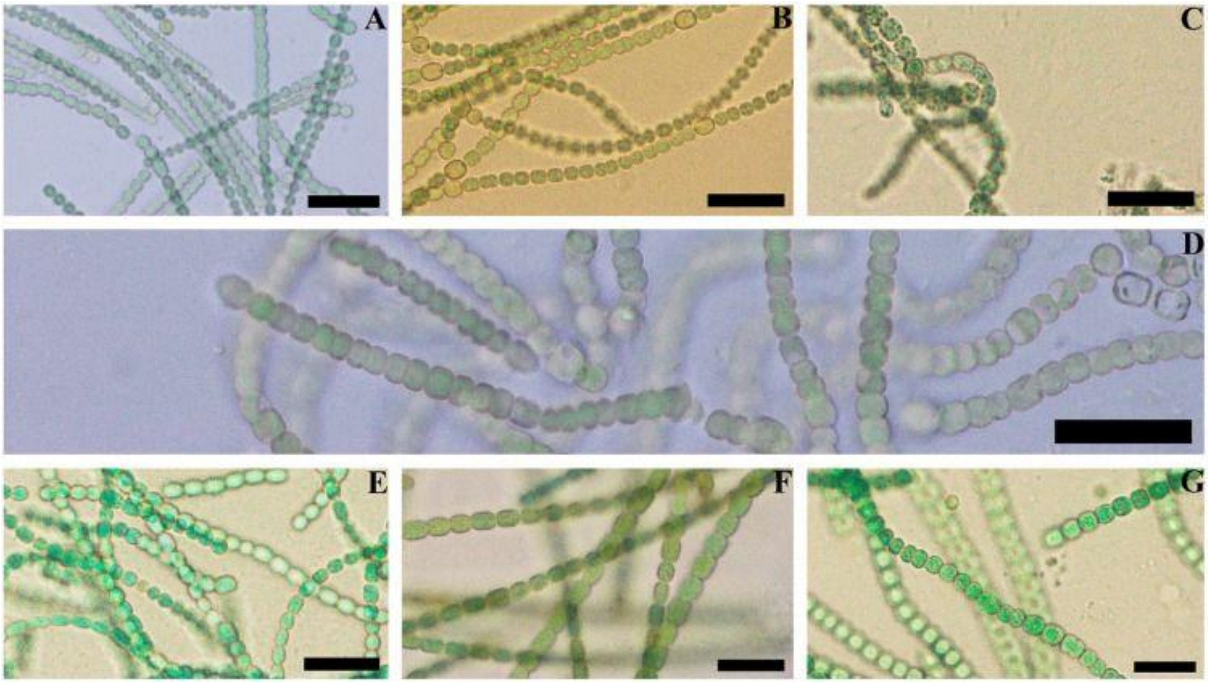

Fig.1. Bright field images representing different filamentous heterocystous cyanobacterial species (Horváth *et al*, 2019).

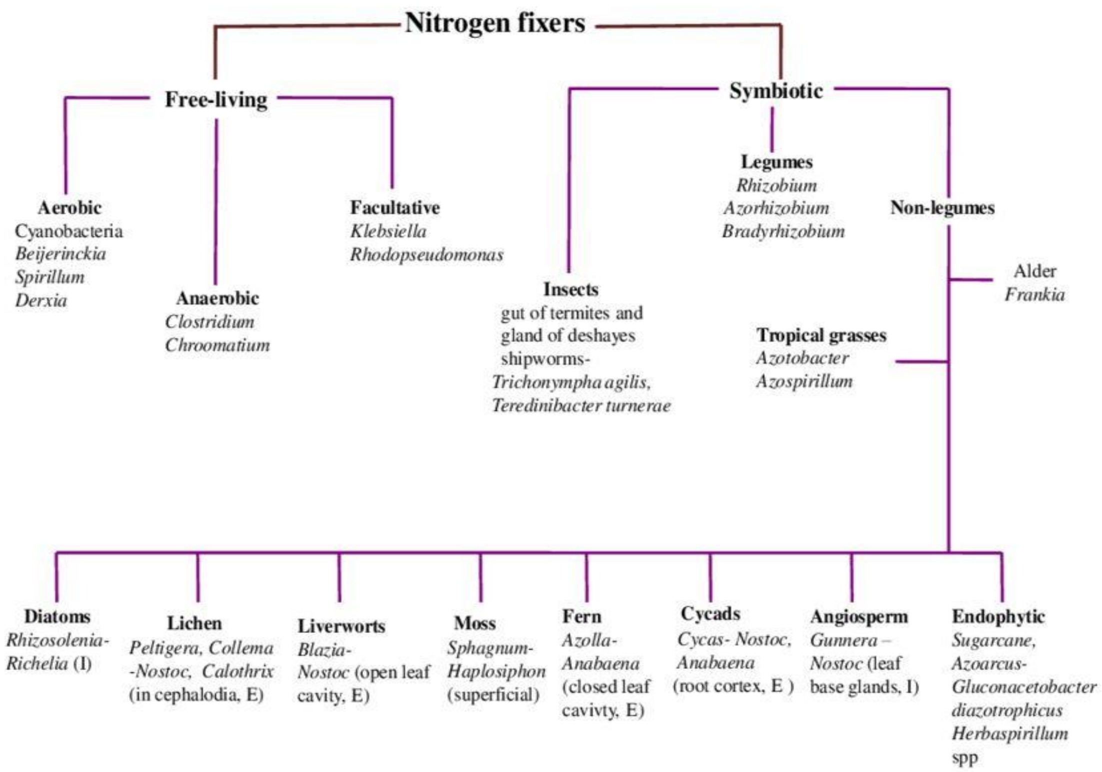

Fig.2. Free-living and associative molecular nitrogen fixers with representative examples (E, extracellular; I, intracellular) (Rai, 2019).

2.1.2. Free-Living Nitrogen-Fixing Cyanobacteria

Known as blue-green algae, they are prokaryotic photosynthetic free-living microorganisms that can fix free atmospheric N_2. This group includes many genera such as *Anabaena*, *Nostoc*, *Aulosira*, *Tolypothrix*, *Cylindrospermum*, and *Stigonema*. Common agricultural practices involve the addition of organic matter and mineral N fertilizers to nourish soil and consequently to enhance plant growth and productivity. However, modern agricultural technologies encourage the application of cyanobacteria as ecofriendly soil additive to fix atmospheric free N_2. For example, *Cylindrospermum licheniforme* grows in sugarcane and maize fields, whereas *Aulosira fertilissima* is recognized as one of the active N_2 fixers in rice fields (Saiz *et al.*, 2019).

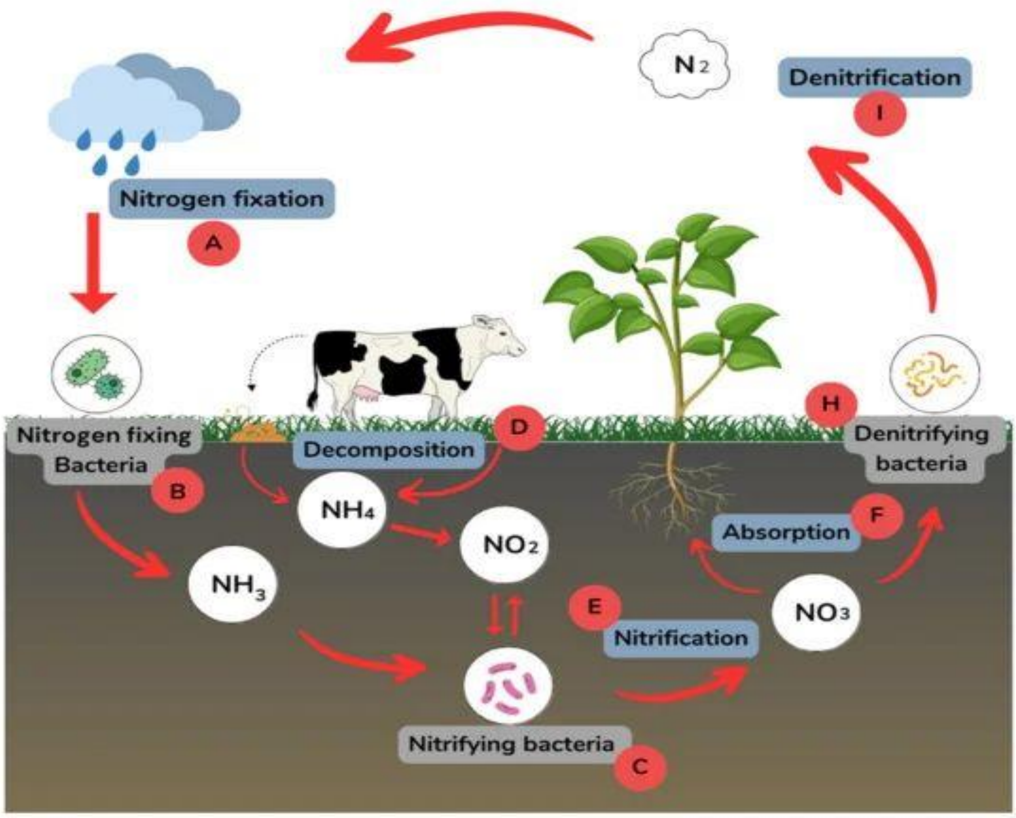

Fig.3. Nitrogen cycle in the environment. (A) Nitrogen fixation, (B) Nitrogen fixing bacteria, (C) Nitrifying bacteria, (D) Decomposition, (E) Nitrification, (F) Absorption, (H) Denitrifying bacteria, and (I) Denitrification. (Geisler *et al.*, 2003).

2.1.3. Symbiotic Nitrogen-Fixing Cyanobacteria

Cyanobacteria develop symbiotic association with non-photosynthetic and photosynthetic species such as fungi, algae, liverworts, hornworts, mosses, bryophytes, pteridophytes, angiosperms, and gymnosperms (Sarma *et al.* 2016). N_2-fixing cyanobacteria form symbiotic associations with several plants, for example, liverworts, cycad roots, lichenized fungi, and *Azolla* (fern). *Azolla pinnata* is a small free-floating freshwater fern found in paddy cultivation, which proliferates rapidly, doubling every 5–7 days, and is found in temperate climate. It fixes N_2 in association with N_2-fixing cyanobacterium, *Anabaena azollae* (Mahanty *et al.* 2017). When *A. azollae* strains encapsulated in foam are introduced into rice fields, cyanobacterium releases ammonium into the water. *Anabaena azollae* fix N_2 and produces specific growth hormones in return for the favorable environment provided by *Azolla* (Singh *et al.* 2016). Fig. 4 shows both symbiotic and non-symbiotic association of N_2 fixing cyanobacteria in soil rhizosphere of leguminous and non-leguminous plants.

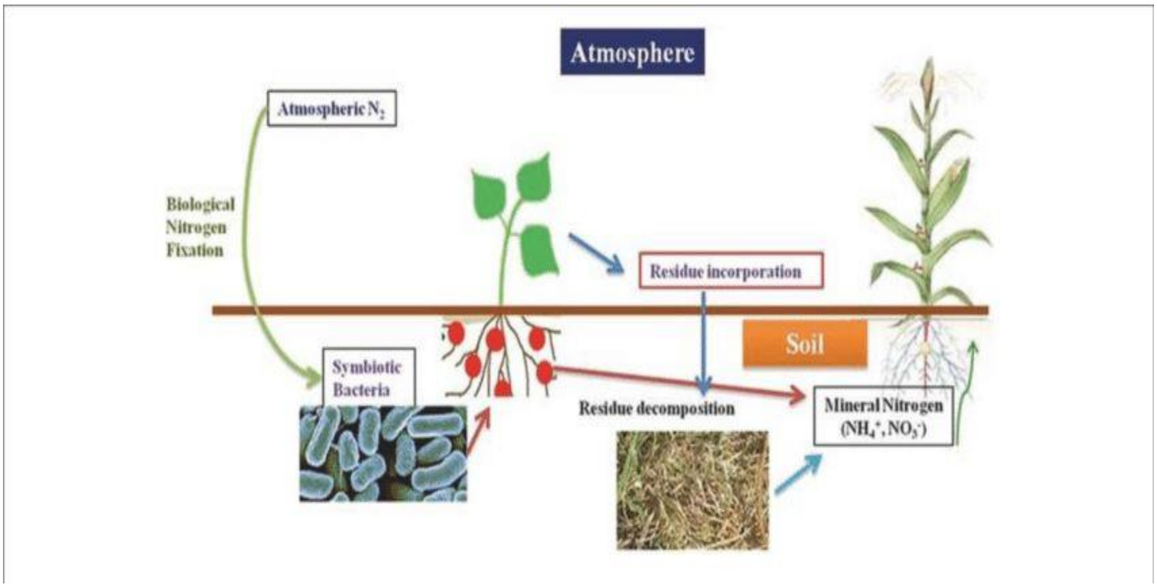

Fig.4. Leguminous green manure crop fixation and mineralization in soil (Means *et al.*, 2018).

2.2. Carbon Dioxide Fixation by Microalgae and Cyanobacteria

It is recognized that the primary cause of climate change is the buildup of greenhouse gases in the atmosphere because of industrialization and human activity (IPCC *et al.*, 2014). The consequences of climate change have risen by 43% since 1990 because of greenhouse gas emissions, of which carbon dioxide (CO_2) makes up about 82% (WMO, 2019). From August 1 to August 17, 2015, atmospheric CO_2 levels were nearly 400 parts per million (ppm) in almost every area on Earth (Cressie, 2018). According to the World Meteorological Organization's Greenhouse Gas Bulletin, the average global CO_2 concentration in 2018 was 407.8 parts per million, which exceeds the 405.5 parts per million recorded in 2017 (Global Monitoring Laboratory, 2020; WMO, 2019).

The energy consumption of carbon capture is still a significant problem, despite reports that the production capacity of global carbon capture demonstration projects (such as those producing plastics, biofuels, sodium hydroxide, etc.) has surpassed 700, 000 tons annually (He *et al.*, 2017). When it comes to CO_2 fixation, microalgae that use the same photosynthesis as terrestrial plants have greater benefits than those plants. First, unlike terrestrial plants, microalgae are photoautotrophic, meaning they may directly use dissolved nitrogen (N), phosphorus (P), and organic carbon (OC) instead of relying on a vascular system to deliver nutrients (Klinthong *et al.*, 2015). Second, native microalgae can be cultivated without raising biosafety concerns since the microalgae strains are isolated from the surrounding environment. Microalgae can be found practically anywhere, even in freshwater and saltwater (Kroumov *et al.*, 2016; Singh *et al.*, 2019).

Furthermore, substantial land areas are not required for the large-scale outdoor cultivation of microalgae (Singh *et al.*, 2014). It's possible that microalgal culture technology is the only way to concurrently remove nutrients from wastewater and fix CO_2 (Hariz and Takriff, 2017; Wang *et al.*, 2018). It has been demonstrated that wastewater from cities, farms, and industries can be used as a source of nutrients to grow microalgae at low affordable without generating excessive amounts of secondary pollution or energy consumption (Arun *et al.,* 2017; Bilad *et al.,* 2014). As a result, SundarRajan *et al.*, (2019) believed that the unique qualities of microalgae cultivation which include the ability to use nutrients for growth have made them a well-known wastewater treatment technique.

Wide-ranging of applications in CO_2 fixation, waste-water treatment, industrial use, and their by-products have been made possible by recent advancements in microalgal culture technology research (Shen, 2015; Yadav *et al.,* 2015; Zhou *et al.,* 2017). Because of these uses, researchers are focusing more on identifying new species of microalgae, refining photobioreactors (PBRs), and increasing the output of byproducts like protein and bio-oil (Razzak *et al.,* 2013; Ruangsomboon *et al.,* 2017).

Nevertheless, studies on the kinetics and processes of microalgae employed in CO_2 fixation in conjunction with wastewater treatment are still in their infancy, and there is currently a paucity of reliable data in this area. Furthermore, because the nature of the microalgae, environmental factors, and breeding mode generally determine the efficiency of microalgae applied in CO_2 fixation coupled with wastewater treatment, a fundamental understanding of the interactions among microalgae growth characteristics, external environmental factors, and breeding modes is also vital to the further design of highly efficient applications in industry.

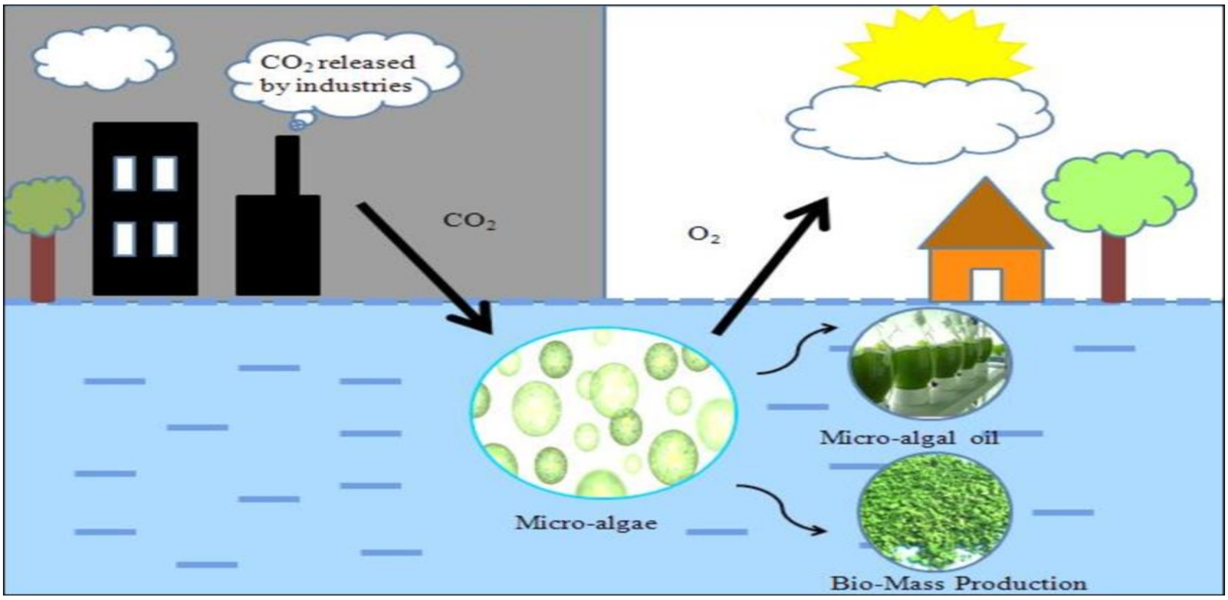

Fig.5. A-representative diagram showing CO_2 fixation using Microalgae-based-process (Kushwaha *et al*, 2021).

Table 1: Application of microalgae in CO_2 fixation alone

Microalgae	L/ ($\mu mol.m^{-2}.S^{-1}$)	T/ (°C)	Reactor	Time / (days)	References
Chlorella vulgaris	36-126**	22	500 mL flasks	About 11	(Pires *et al.*2014)
Spirulina platensis Spirulina platensis	400	28-30	Flat PBR	na	(Ho *et al.*,2017)
Botryococcus braunii	62.5	25	1L glass flasks	18	(Ruangsomboon *et al.*, 2017)
Scenedesmus obliquus Chlorella kessler	3200*	30	2L conical flask PBR	20	(de Morais and Costa, 2017a)
Spirulina* sp. *Scenedesmus obliquus	3200*	30	2L column PBR	10-21	(de Morais and Costa, 2017b)
***Chlorella* sp.**	160.6	28	Bubble column reactor (0.5 L)	7	(Yadav and Sen,2017).
***Chlorella* sp. *Scenedesmus* sp.**	4320*	27	Tubular PBR	6	(Singh *et al.*,2016)
Spirulina platensis Synechococcus* spp. *Scenedesmus	na	AT	Open pond	16	(Eloka-Eboka and Inambao,2017)

2.3. Role of microalgae and cyanobacteria in formation of soil crusts:

Over 38% of all people live in dry and semi-arid regions which make up to 41% of the world's land area. Due to climatic change, human activity, and other reasons, roughly 25% of the world's land surface is affected by desertification and about 40% of the planet's terrestrial area is at risk of desertification (Perera *et al.*, 2018). The existence of organic soil crusts is one of these drylands' notable characteristics (Belnap *et al.*, 2016).

Soil crust is the hardest soil surface could be biological soil crust or physical soil crust. The biological soil crust (Biocrust) is found in arid and semiarid areas and is found as group of living organisms in which each species has specific important functions, and those organisms may make up as much as 70% of the living soil. Biological soil crust organisms are often fungi, cyanobacteria, algae, and lichens.

The physical soil crust is affected by nature or other environmental reasons such as raindrops, wind action and sedimentation. physical soil crust becomes hard and more compact when they dry as also their thickness varies.

Among these arid regions notable characteristics are observed due to presence of biological soil crusts, which is found in two types: Microscopic cyanobacteria, algae, fungi, and bacteria, comprising hypoliths as it called biocrusts, and poikilohydric organisms which are made up of macroscopic lichens, mosses, and microarthropods, the biocrusts affect the atmospheric fixation of carbon (C) and nitrogen (N), which in turn determines the soil's structure, organic matter and other resources, capture and retention, surface morphology and fertility (Belnap *et al.,* 2016).

Cyanobacteria in biocrust play essential roles in stabilizing soils by using extracellular matrix to glue and create soil aggregates, as an example *Microcoleus* in which a hardened surface layer consisting of inorganic soil matter and living organisms is the end result. This crust plays a major role in protecting arid soils from wind and water erosion, also play a role in facilitating the cycling of C and N so they can convert them into a form that can be used by plants as shown in Fig. 6 , as an example *Chroococcidiopsis* sp. and *Myrmecia* sp. (Büdel *et al.,* 2016).

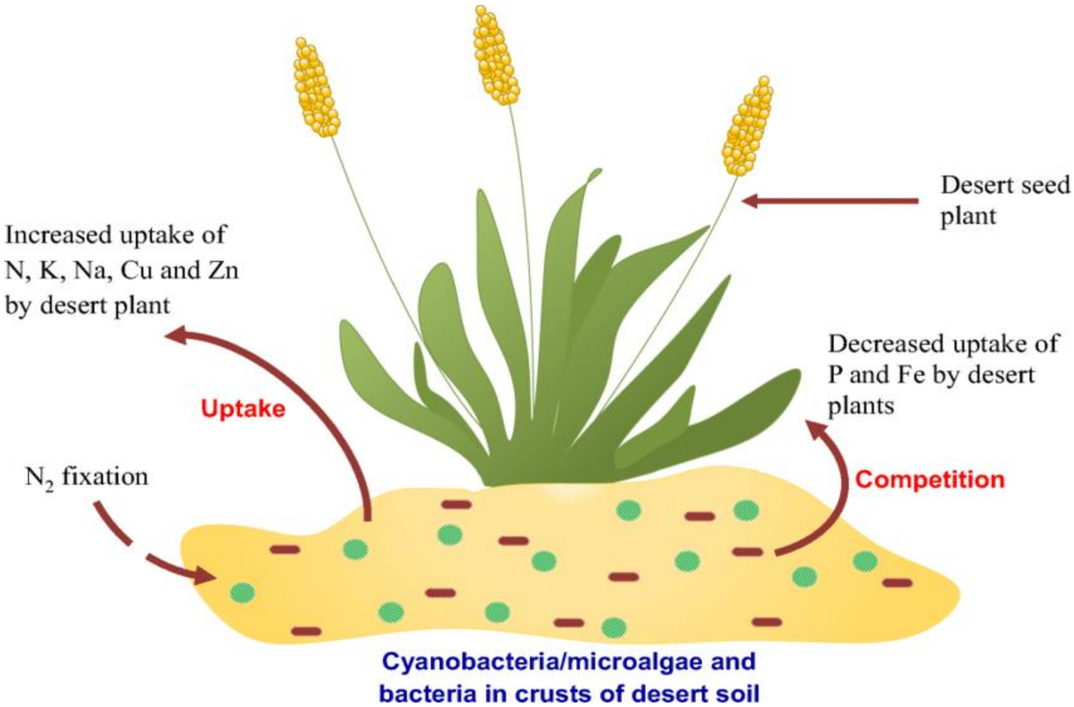

Fig. 6. The presence of cyanobacteria and microalgae enhance uptake of nutrients (Perera *et al.*, 2018).

Cyanobacterial extracellular polymeric substances (EPS) forms permanent organo-mineral layers, it is vital for the improvement of dryland soils, this is made possible by the interaction of EPS with cyanobacterial trichomes which link soil fragments together and produce a layer that protects against erosion and desiccation. EPS is a type of highly hydrated polymer mostly made up of proteins, DNA, and polysaccharides (Costa *et al.*, 2018).

Other microorganisms that occur in biocrusts are eukaryotic microalgae in which fall into the following main functional groups. Variety of algae can form crusts in different ways by being filamentous or secreting mucilage exudates such as *Klebsormidium* sp. and *Zygogonium*or sp. or by adhering to soil particles and forming crusts like *Spongiochloris* sp., also may occur within lichens as symbionts *e.g.* *Myrmecia* (Büdel *et al.*, 2016).

2.4. Uptake of phosphate (phosphate solubilization):

Photoautotrophic microorganisms such as cyanobacteria and microalgae are currently being grown for their high-value products, which include vitamins, proteins, fatty acids, pigments, and polysaccharides (Borowitzka, 2013; Spolaore *et al.*, 2006). In addition, it's thought that microalgae will be very important in the renewable energy sector and that they might be used as a biomass feedstock for the manufacturing of biofuels (Gouveia,2011; Schenk *et al.*, 2008; Hamed *et al.*, 2022a).

2.4.1. phosphorus as element in the nature:

Phosphorus is essential element for the development of plants, and a number of functions including respiration, photosynthesis, energy control, and macromolecule production (Ray *et al.*, 2013). Phosphorus (P) makes up around 0.2% of a plant's dry weight and is one of the essential elements required for plant growth and development as shown in Fig.7 (Azziz *et al.*, 2012; Tak *et al.*, 2012). Total P is found in most soils at higher concentrations than other important nutrients like potassium (K) and nitrogen (N), nevertheless over 80% of P is difficult to be absorbed by plants (Crews and Brookes ,2014; Qaswar *et al.*,2020).

Thus, a possible method for enhancing plant absorption of phosphate is to inoculate soil or crops with P-solubilizing/mineralizing microorganism and thereby lessening the need for environmentally harmful chemical fertilizers (Alori *et al.*, 2012).

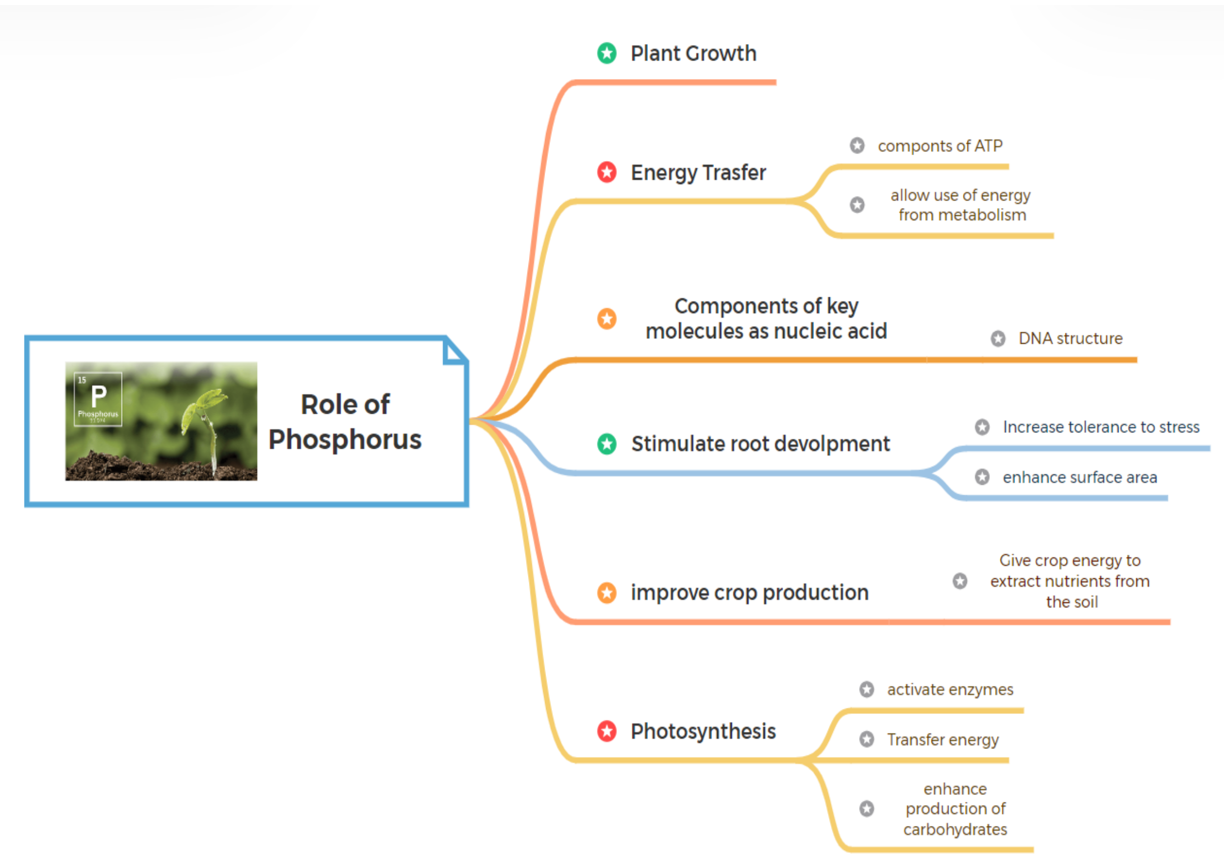

Fig.7. Role of phosphorus in enhancing plant growth

2.4.2. Microalgae and Cyanobacteria Aid in Phosphate Solubilization:

A rich source of diversity in the microbiome is the soil, organisms known as phosphate solubilizing microorganisms (PSMs). These microorganisms can transform insoluble phosphorus into a soluble form available for plants uptake as shown in Fig.8. These kinds of microorganisms can be employed as an efficient biofertilizer. They are abundant in soil at both qualitative and quantitative levels, and can be used to assess their potential for P solubilization (Mehta and Nautiyal,2001; Ramakrishnan *et al*., 2023).

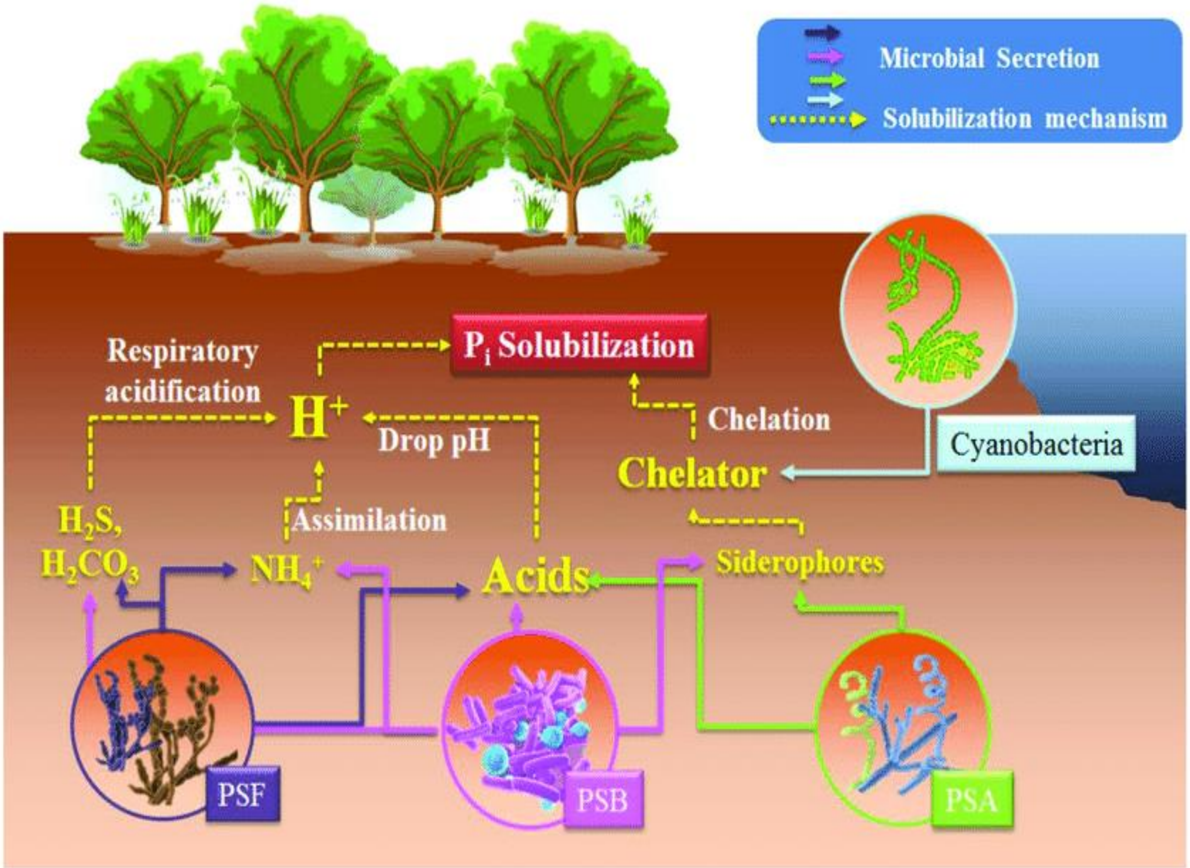

Fig.8. Role of microorganisms including cyanobacteria in phosphate solubilizing solubilization (Tian *et al.*, 2021).

It has been demonstrated that PSMs separated from bulk soils and rhizospheres hydrolyze organic P by releasing phosphatases (Bi *et al*., 2018). Phosphatases are the enzymes that catalyze the hydrolysis of phosphoric acid esters and anhydrides, which causes organic P decomposition and mineralization. They are typically categorized as phosphodiesterases, phosphomonoesterases, and enzymes that act on P-N bonds or phosphoryl-containing anhydrides (Nannipieri *et al*., 2011).

Thus, in modern agricultural technology, enhancing crop productivity through the use of P-biofertilizers is a promising way to increase food supply, as it is preferable to employ an environmentally friendly method (Babalola and Glick, 2012a). The ability to solubilize and mineralize P has been shown by a wide range of microbiological species, including actinomycetes, bacteria, fungi, and algae (Babalola and Glick, 2012b). Since P is a limiting element for crop growth and productivity. Therefore, soil P availability is a key factor in global food security (Cordell *et al.*, 2011).

Using algae and cyanobacteria as biostimulants and biofertilizers on various crops has become more important which can reduce the use of chemical fertilizers and lead to higher crop yields. They are essential in soil structure, reducing the need for heavy chemical treatment, monitoring soil erosion, restoring damaged ecosystems, and reducing greenhouse gas emissions (Renuka *et al.*, 2018).

Additionally, it has been demonstrated that cyanobacteria may solubilize less soluble forms of P in soil sediments, or pure cultures, including calcium phosphate [$Ca_3(PO_4)_2$], ferric phosphate ($FePO_4$), aluminum phosphate ($AlPO_4$), and hydroxyapatite [($Ca_5(PO_4)_3$.OH)]. This increases the amount of available P to plants (Yandigeri *et al.*, 2011).

As an example of cyanobacteria genera capable of phosphate solubilization are *Anabaena* spp., *Calothrix* spp., *Nostoc* spp., and *Scytonema* spp. (Bispo *et al*. 2023), and microalgae such as *Chlorella* spp (Toribio *et al.* 2020).

It has been reported that *Microcystis aeruginosa*, a prevalent cyanobacterium species possesses genes that encode extracellular alkaline phosphatase, which catalyze solubilization of a range of insoluble inorganic or organic compounds (Xie *et al.*, 2020).

2.5. Role of Microalgae and Cyanobacteria as Plant Biostimulants:

Modern agriculture is showing a great interest in plant biostimulants (PBs) as a means of improving plant performance, resistance to environmental stress, and nutrient use efficiency (Chiaiese *et al.*, 2018), as it can decrease the use of harmful fertilizer. Biostimulants work directly on the plant to increase the production of crops. These substances are involved in increasing ion uptake, respiration process, photosynthesis, nucleic acid synthesis, and metabolism in plants, which in turn promotes plant development as represented in Fig.9 (Górka *et al* 2018; Chabili *et al*., 2024).

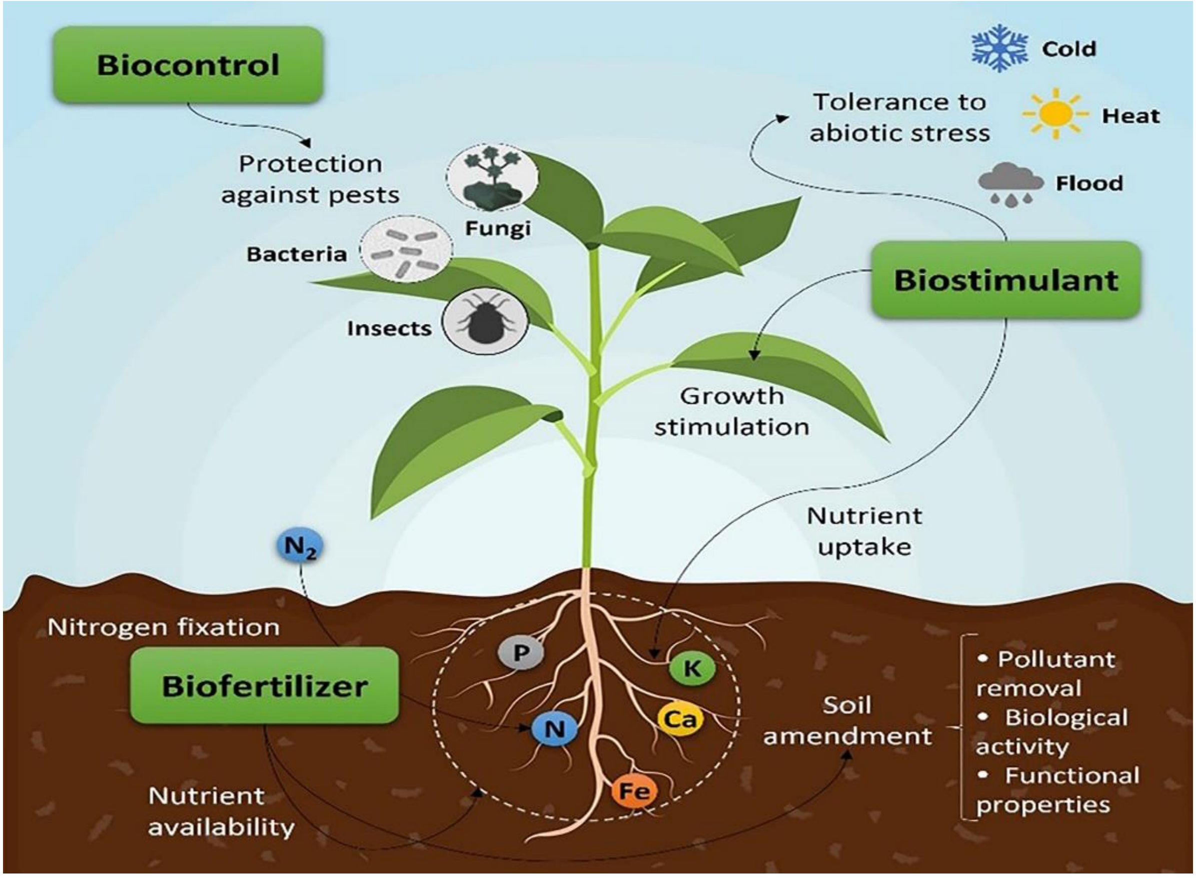

Fig.9. Role of microalgae and cyanobacteria as a biostimulant and biofertilizer and their effect on the plants (Ferreira *et al.*, 2023).

Biostimulants are known as products made from organic compounds that can promote the development and growth of a variety of crops. When they even used in tiny amounts, in both ideal and challenging environments, they significantly increase plant growth and productivity (Ronga *et al*., 2019).
These substances in fact may enhance plant growth and productivity with fewer adverse impacts on the environment (Ertani *et al*., 2015).

Microalgae and cyanobacteria constitute a significant source of phenolic compounds, polysaccharides, hormone-like substances (phytohormones), and proteins. These compounds are well-known for their inducive effect as antioxidants and promoters of plant growth. Furthermore, the significance of living organisms in fertilizing soils and promoting plant growth is well acknowledged. Prokaryotes such as nitrogen-fixing cyanobacteria and eukaryotes such as microalgae and macroalgae/seaweeds have been well documented as excellent natural biostimulants under field conditions (Chiaiese *et al.*, 2018; Hamed and Messiha, 2023).

The focused use of microalgae in crop science is still in its early stage, despite the fact that it is well recognized that they produce a number of complicated macromolecules that are effective on higher plants (Chiaiese *et al.*, 2018). Biologically active metabolites produced by microalgae and cyanobacteria are shown in Table 2 below. Previous reports indicated that microalgal extracts, the kind of microalgal species and the extraction method employed have a significant impact on the amount and quality of bioactive components (Puglisi *et al.*, 2018).

Table 2 : Primary biologically active substances isolated from cyanobacteria and microalgae to be used in agriculture activities.

Compounds	**Examples**	**Microalgae, cyanobacteria examples**	**Agricultur e Functions**	**References**
Phytohormones	Auxins abscisic acid cytokinin ethylene gibberellins	*Arthrospira Chlamydomonas Chlorella Phormidium Protococcus Scenedesmus*	Stimulate plant growth, Control cell activity, enhance stresses reaction	(Han *et al*., 2018) (Lu *et al*., 2015) (Ronga *et al*., 2019) (Singh *et al*., 2017) (Pan *et al*., 2019) (Ördög *et al*.,2004)
Free fatty acid	Saturated, unsaturated fatty acid	*Anabaena Chlorella Dunaliella Nannochloropsis Porphyridium Scenedesmus Spirulina*	Deffence against disesses and other biotic and abiotic stress	(Demirbas *et al*., 2011) (Desbois *et al*.,2010) (El-Baz *et al*., 2013) (Feller *et al*., 2018) (Lam *et al*., 2012) (Singh *et al*., 2017) (Pan *et al*., 2019)
Terpenoids	Hemiterpenes monoterpenes sesquiterpen diterpenes triterpenes polyterpenes	*Chondrococcus hornemanni* , *Hypnea pannosa Oscillatoria perornata* , *Planktothricoids raciborskii*, *Plocamium cornutum*	Defences ,stmulate plant growth and pollinators attraction	(Awasthi *et al*., 2018) (Singh *et al*., 2017)
Polysaccharides	Extracellular polysaccharid, Structural polysaccharid, Energy-storage polysaccharid	*Aphanothece Arthrospira Chlamydomonas Chlorella Cylindrotheca*	Enhance soil quality and growth	(Campos *et al*., 2015) (El Arroussi *et al*., 2018) (Singh *et al*., 2017)
Phenolic Substance	Polyphenols Phenolic acids Flavonoids Phenylpropan-oids	*Botryococcus braunii*, *Chlorella vulgaris*	Protect and defense against pathogen	(Esquivel-Hernández *et al*., 2017) (Foo *et al*., 2017) (pan *et al*., 2019)

Microalgal extract generally contains carbohydrates and lipids in large content. The role of microalgae and cyanobacteria as plant biostimulants may reach up to 46% of their dry weight (DW) (Spolaore *et al.*, 2006; Pinzón *et al*., 2014; Tibbetts *et al*., 2015). Tryptophan and arginine are two amino acids that are the metabolic precursors of important phytohormones, hence it is believed that their presence in microalgal extracts will greatly enhance crop development and output (Colla *et al*., 2013; Colla *et al*., 2014; Colla *et al*., 2016).

Microalgae and cyanobacteria make necessary phytohormones that support plant development include auxin that increase oil content, growth rate, biomass results, and stress tolerance , also cytokinin which is improve the rate of growth, raise oil content, encourage division of cells in plant roots and shoots, and increase stress tolerance, and ethylene in which is contributes to the production of biomass, enhanced growth rates, and participate in programmed cell death (Baweja *et al*., 2019; Kumar *et al*., 2018; Rai *et al*., 2019).

2.6. Role of Microalgae and Cyanobacteria in Degradation of Agrochemicals

Agrochemicals are usually defined as pesticides, fertilizers, and health products. The U.S. Environmental Protection Agency (EPA) defines pesticides as any substances manufactured or formulated to kill pests. This means that herbicides, fungicides, insecticides, and insecticides are pesticides. Fertilizers are nutrient chemicals that promote plant growth. Agrochemicals, including pesticides, herbicides, and fertilizers, play a crucial role in modern agricultural practices, ensuring high crop yields and protection against pests and diseases. However, the indiscriminate use of these chemicals has led to significant environmental concerns, including soil and water pollution, biodiversity loss, and potential human health risks (Aktar *et al.*, 2009).

The persistence of agrochemicals in the environment and their potential for bioaccumulation and biomagnification in the food chain have prompted researchers to explore eco-friendly and sustainable methods for their degradation and removal.

In recent years, microalgae and cyanobacteria have emerged as promising bioremediation agents for the degradation of agrochemicals as shown in Fig.10. These photosynthetic microorganisms possess unique metabolic pathways and enzymatic systems that enable them to degrade and transform a wide range of organic pollutants, including agrochemicals (Pinto *et al.*, 2003; Sahin *et al.*, 2018). This article provides an overview on the role of microalgae and cyanobacteria in the degradation of agrochemicals, highlighting their mechanisms, potential applications, and future prospects.

Numerous organophosphate and carbamate bug sprays are especially vulnerable to hydrolysis under basic circumstances. Some are separated inside merely hours when blended in with antacid water (Touliabah, 2022)

The breakdown of pesticides by light, particularly sunlight, is known as photodegradation. Pesticides on foliage, the surface of the soil, and even in the air can be destroyed by photodegradation. The intensity of the sunlight, the characteristics of the application site, the application method, and the characteristics of the pesticide are all factors that influence the photodegradation of the pesticide. More than 33% of Missouri's populace, including around 95% of the state's provincial populace, depends on groundwater as a wellspring of drinking water. Most Missourians get their water from a variety of surface water sources. Road salts, agricultural fertilizers, and pesticides, leaking underground fuel storage tanks, and industrial and municipal waste all have the potential to contaminate these water supplies (Touliabah, 2022).

In the next lines we will discuss the important role of microalgae and cyanobacteria in biodegradation of a wide range of agrochemicals and emerging contaminants that are commonly found in soils and water webs due to agricultural activities.

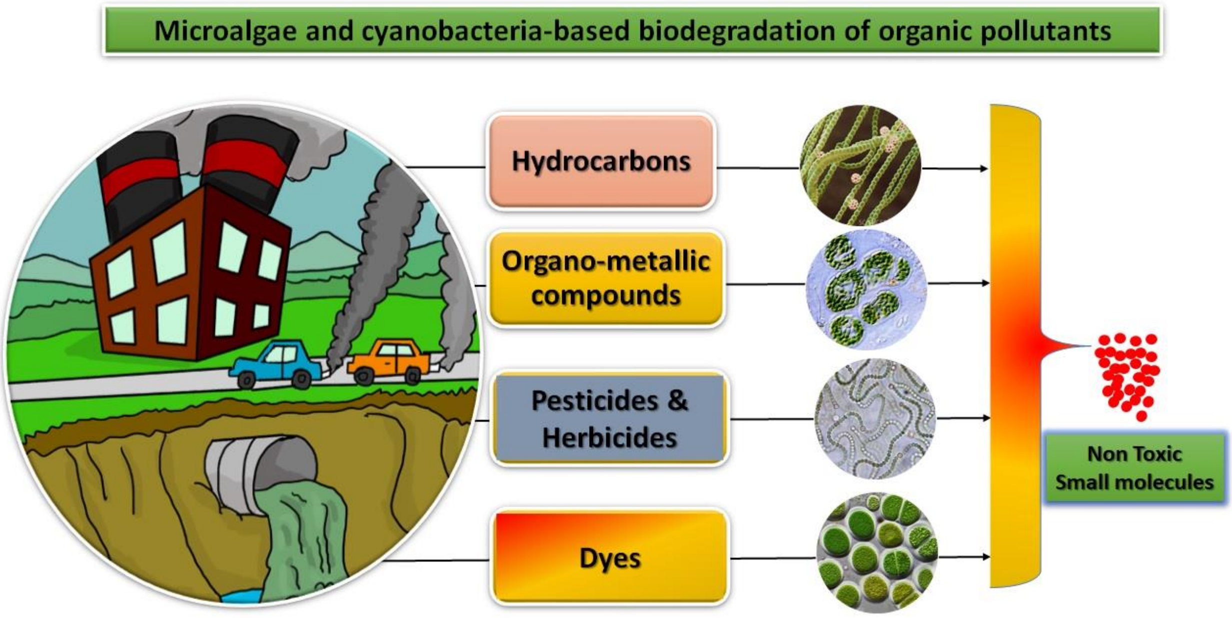

Fig.10. Role of microalgae and cyanobacteria in agrochemical biodegradation (Touliabah *et al.*, 2022).

2.6.1. Mechanisms of Agrochemical Degradation by Microalgae and Cyanobacteria

Microalgae and cyanobacteria employ various mechanisms to degrade and transform agrochemicals, including enzymatic degradation, photodegradation, and biosorption (Sahin *et al.*, 2018; Mohapatra and Kirpalani ,2021).

2.6.1.1. Enzymatic Degradation:

These microorganisms possess a diverse array of enzymes, such as oxidoreductases, hydrolases, transferases, and lyases, which can catalyze the transformation and breakdown of agrochemicals. For example, the enzyme systems of microalgae like *Chlorella vulgaris* and *Scenedesmus* obliquus have been found to be effective in degrading various pesticides, including atrazine, diuron, and chlorpyrifos (Pinto *et al.*, 2003; Mohapatra and Kirpalani,2021).

2.6.1.2. Photodegradation:

Microalgae and cyanobacteria can utilize light energy for the photodegradation of agrochemicals. This process involves the generation of reactive oxygen species (ROS), such as singlet oxygen, superoxide radicals, and hydroxyl radicals, which can initiate the oxidation and degradation of agrochemicals (Sahin *et al.,* 2018; Shen *et al.,* 2022).

2.6.1.3. Biosorption:

Microalgae and cyanobacteria possess a high surface area-to-volume ratio, enabling them to adsorb and concentrate agrochemicals from the surrounding environment. This process, known as biosorption, can facilitate the subsequent degradation of agrochemicals by the enzymatic systems of these microorganisms (Mohapatra and Kirpalani,2021; Shen *et al.*, 2022).

2.6.2. Application of Microalgae and Cyanobacteria in Agrochemical Degradation

The ability of microalgae and cyanobacteria to degrade agrochemicals has led to their application in various bioremediation strategies, including wastewater treatment, soil remediation, and phytoremediation (Aksu and Tezer ,2005; Sahin *et al.*, 2018; Mohapatra and Kirpalani,2021).

2.6.2.1. Wastewater Treatment:

Microalgae and cyanobacteria have been employed in the treatment of agrochemical-contaminated wastewater from agricultural runoff, industrial effluents, and municipal wastewater treatment plants. These microorganisms can effectively degrade and remove agrochemicals, reducing their environmental impact on receiving water bodies (Aksu and Tezer ,2005; Sahin *et al.*,2018).

2.6.2.2. Soil Remediation:

The application of microalgae and cyanobacteria, either as single strains or as consortia, can facilitate the degradation of agrochemicals in contaminated soils. This approach not only remediates the soil but also enhances soil fertility by improving nutrient availability and soil structure (Mohapatra and Kirpalani ,2021; Shen *et al.*,2022).

2.6.2.3. Phytoremediation:

Microalgae and cyanobacteria can be used in conjunction with higher plants in phytoremediation systems. These microorganisms can enhance the degradation of agrochemicals in the rhizosphere (root zone) and facilitate the uptake and translocation of degradation products by the plants (Mohapatra and Kirpalani,2021; Shen *et al.*,2022).

2.6.3. Degradation of fungicides

Microalgae and cyanobacteria address a potential new choice for the bioremediation of refinery wastewaters since they have trophic freedom for nitrogen uptake. In any case, since they are light-reliant responses, weakening of the shaded effluents to be dealt with is expected to keep away from light blockage. Because of the rising utilization of hydrocarbon squander and other natural poisons in different frameworks, they have become one of the world's most serious ecological challenges.

Bioremediation of different natural toxins by microalgae and cyanobacteria is an economical and ecologically satisfactory green innovation for the treatment of contaminated water that has a lesser ecological effect than different microorganisms and customary techniques (Hamed *et al.*, 2020; Hamed *et al.*, 2024).

Moreover, these pollutants advance the development of algal biomass, which can be taken advantage of in different courses from here on out. To handle this trouble, future endeavors will be made to evaluate more green growth strains for phytoremediation, as well as hereditary designing to further develop algal biodegradation capacity and resilience to different natural impurities (Touliabah, 2022).

Fungicides are widely used in modern agriculture to protect crops from fungal pathogens and ensure high yields. However, their indiscriminate use and persistence in the environment have raised concerns about their potential adverse effects on non-target organisms and ecosystems (Aktar *et al.*, 2009). Traditional methods for fungicide removal, such as chemical treatment or incineration, can be costly and environmentally damaging (Mohapatra and Kirpalani,2021).

As a result, there is a growing interest in exploring eco-friendly and sustainable approaches for fungicide degradation, including the use of microalgae and cyanobacteria.

2.6.3.1. Mechanisms and examples of Fungicide Degradation by Microalgae and Cyanobacteria

Microalgae and cyanobacteria possess unique metabolic pathways and enzymatic systems that enable them to degrade and transform a wide range of organic pollutants, including fungicides. The primary mechanisms involved in fungicide degradation by these microorganisms include enzymatic degradation, photodegradation, and biosorption (Sahin *et al.*, 2018; Shen *et al.*, 2022).

Microalgae and cyanobacteria possess a diverse array of enzymes, such as oxidoreductases, hydrolases, transferases, and lyases, which can catalyze the transformation and breakdown of fungicides. For example, the green alga *Chlorella vulgaris* has been shown to degrade the fungicide carbendazim through the action of enzymes like cytochrome P450 monooxygenases and glutathione S-transferases (Mohapatra and Kirpalani, 2021). Similarly, cyanobacteria like *Anabaena cylindrica* and *Nostoc muscorum* have exhibited the ability to degrade fungicides like captan and carbendazim through their enzymatic systems (Mohapatra and Kirpalani, 2021). While in photodegrading microalgae and cyanobacteria can utilize light energy to generate reactive oxygen species (ROS), such as singlet oxygen, superoxide radicals, and hydroxyl radicals, which can initiate the oxidation and degradation of fungicides. The photosynthetic pigments in these microorganisms, like chlorophyll and carotenoids, can act as photosensitizers, facilitating the generation of ROS (Sahin *et al.,* 2018; Mohapatra and Kirpalani 2021).

In other hand, biosorption in which microalgae and cyanobacteria possess a high surface area-to-volume ratio, enabling them to adsorb and concentrate fungicides from the surrounding environment. This process, known as biosorption, can facilitate the subsequent degradation of fungicides by the enzymatic systems or photodegradation processes within these microorganisms (Sahin *et al.,* 2018; Mohapatra and Kirpalani ,2021).

Efficiency of fungicide degradation by microalgae and cyanobacteria is influenced by various factors, including the specific microalgal or cyanobacterial species, the type and concentration of fungicides, environmental conditions, and the presence of other microorganisms (Shen *et al.*, 2022).

Different species of microalgae and cyanobacteria exhibit varying levels of efficiency in degrading specific fungicides due to their unique metabolic capabilities and enzymatic systems. For instance, *Chlorella vulgaris* and *Scenedesmus obliquus* have shown significant degradation potential for fungicides like carbendazim and captan (Mohapatra and Kirpalani,2021).

The chemical structure and concentration of the fungicide can affect the degradation efficiency. Some fungicides may be more recalcitrant and resistant to degradation compared to others (Shen *et al.,* 2022). Higher concentrations of fungicides can also inhibit the growth and metabolic activity of microalgae and cyanobacteria, thereby reducing their degradation potential (Mohapatra and Kirpalani, 2021).

Factors such as temperature, pH, light intensity, and nutrient availability can influence the growth and metabolic activities of microalgae and cyanobacteria, ultimately affecting their ability to degrade fungicides. Optimal environmental conditions are critical for maximizing the degradation efficiency (Shen *et al.,* 2022).

The degradation of fungicides can be enhanced by using consortia of microalgae, cyanobacteria, and other microorganisms like bacteria or fungi as shown in Table 3. These consortia can exhibit synergistic effects, with different microorganisms contributing to the degradation process through their unique metabolic pathways and enzymatic systems (Sahin *et al.*, 2018; Mohapatra and Kirpalani, 2021)

Table 3. The removal efficiency of organic pollutants using microalgae on a laboratory scale (Touliabah *et al.*, 2022).

Pollutant	**Algae species**	**Organic pollutants**	**Degradation**
Dyes	*Chlorella spp.* *Chlorella vulgaris* *Sc. Bijugatus* *Volvox aureus*	Pyrene Azo dye Tartrazine Basic cationic (10 ppm)	78.71 ≥90 57 82
Hydrocarbon	*Chlorella spp.* *Sc. Obliquus-bacterial consortium*	Pyrene Oil wastes	78.71 84.2
Phenols	*Ankistrodesumus braunii and Sc. Quadricauda*	phenols	70
Pesticides	*Nannochloris oculata*	Lindane (0.1mg/L)	73
	Chlamydomonas reinhardtii	Isoproturon(50 ug/L)	15.1

2.6.4. Degradation of Pesticides

Algae and cyanobacteria can also break down pollutants by excreting enzymes that break down toxic compounds into simpler, less harmful ones show in Table 4. The capacity of *Scenedesmus quadricauda* to debase Responsive Blue 19 and Remazol Splendid Blue R color (RBBR) in different amphibian conditions was talked about. They carry out photosynthesis by their photosynthetic pigments producing photosynthates. Their essential jobs in the supplement cycle and oxygen creation are significant in numerous environments.

Biomass from microalgae has been used as an adsorbent. *Scenedesmus quadricauda* is a newbie to biosorption research. They utilize light rather than carbon sources like microbes and growth, permitting them to make do without a trace of natural carbon. Subsequently, utilizing metabolically dynamic microalgal frameworks might be more straightforward (Touliabah, 2022).

Table 4 . Examples of Pesticides degradation by microalgae and cyanobacteria (Singh *et al.*, 2020)

Pesticides	**Microalgae/caynobacteria**	**References**
Prometryne,	*Chlamydomonas reinhardtii*	(Chekroun *et al.*, 2014)
fluroxypyr		
isoproturon		
Bisphenol A	*Monoraphidium braunii*	(Gattullo *et al.*, 2012)
alpha-endosulfan, mirex	*Chlorococcum sp.*	(Sethunathan *et al.* ,2004؛Kobayashi and Rittmann ,1982)
α-endosulfan	*Scenedesmus sp.*	(Sethunathan *et al.*, 2004)
Dimethomorph and pyrimethanil	*Scenedesmus quadricuda*	(Dosnon-Olette *et al.*, 2010 a,b)
Atrazine	*Chlamydomonas mexicana*	(Kabra *et al.*,2014)
Malathion	*Chlorella vulgrais, Scenedesumus quadricuda, and Spirulina platensis*	(Abdel-Razek *et al.*, 2019)
DDT	*Chlorococcum sp., Anabaena sp., and Nostoc sp.*	(Megharaj *et al.*, 2000)
DDT, parathion	*Scenedesmus obliquus*	(Kobayashi and Rittmann ,1982)
Atrazine	*Isochrysis galbana, Dunaliella tertiolecta, Phaeodactylum tricornutum, Pseudokirchneriella subcapitata and Synechococcus sp.*	(Weiner *et al.*, 2004)
Diclofop-methyl	*Chlorella vulgrais, Chlorella pyrenoidosa and Scendesmus obliquus*	(Cai ,2007)

Fenamiphos	*Pseudokirchneriella subcapitata, Chlorococcum sp*	(Caceres *et al.*, 2008)
Mirex	*Dunaliella sp*	(Rath, 2012)

2.6.5. Degradation of Agrochemicals

Green growth and cyanobacteria can corrupt poisons through the discharge of explicit catalysts, like azo-color reductase, and convert colors to straightforward, nontoxic mixtures, like NH_2 and CO_2. Little exploration has been directed toward the effectiveness of phytoremediation in lessening supplement levels in eutrophic lakes see Fig.11 (Chabili, 2024).

The use of microalgae and cyanobacteria in the degradation of agrochemicals offers several advantages over conventional remediation methods, including their eco-friendly nature, cost-effectiveness, and potential for simultaneous bioremediation and biomass production (Pinto *et al.,* 2003; Sahin *et al.*, 2018; Mohapatra and Kirpalani, 2021).

However, the application of these microorganisms also faces several challenges, such as the need for optimization of growth conditions, potential toxicity of agrochemicals to the microorganisms, and the potential release of degradation products into the environment (Pinto *et al.*, 2003; Sahin *et al.*, 2018; Mohapatra and Kirpalani, 2021).

The potential of microalgae and cyanobacteria in the degradation of agrochemicals has opened new avenues for sustainable and eco-friendly bioremediation strategies. However, further research is needed to address the challenges associated with their large-scale application, such as optimizing growth conditions, enhancing degradation efficiency, and developing appropriate bioreactor designs (Pinto *et al.*, 2003; Sahin *et al.*, 2018; Mohapatra and Kirpalani, 2021).

Additionally, the integration of microalgae and cyanobacteria with other bioremediation approaches, such as the use of bacteria, fungi, or enzymatic systems, could potentially enhance the overall degradation efficiency and broaden the spectrum of agrochemicals that can be effectively degraded (Mohapatra and Kirpalani,2021; Shen *et al.*, 2022).

Microalgae and cyanobacteria hold significant promise as bioremediation agents for the degradation of agrochemicals, contributing to the development of sustainable agricultural practices and the protection of the environment.

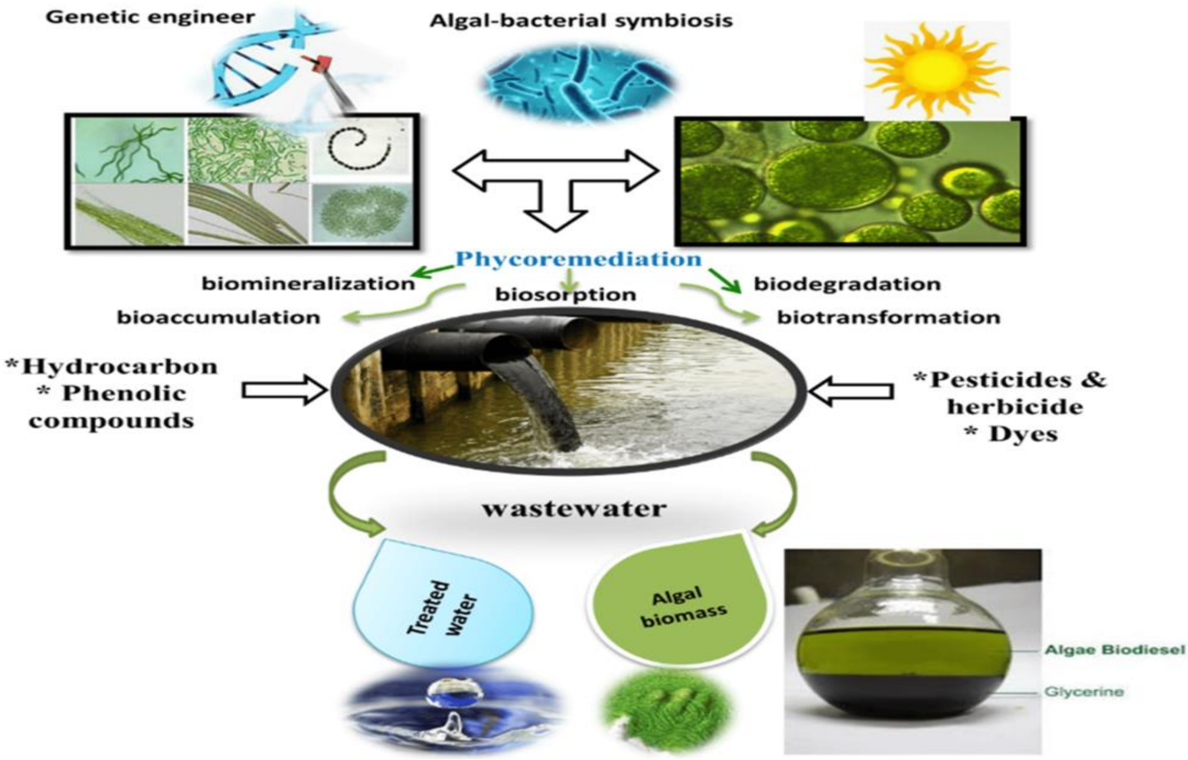

Fig.11. Phytoremediation of organic pollutants by microalgae, cyanobacteria, and biomass utilization (Touliabah *et al.*, 2022).

2.7. Cyanobacteria and Microalgae in Reclamation of Salt-Affected Soils:

Cyanobacteria are a very large group of photoautotrophic prokaryotes. They are a group of photosynthetic bacteria; they can adapt to oxygen-deficient environmental conditions. Some species can live in a variety of diverse mycorrhizal fungi, either freely or in a symbiotic relationship with plants or fungi and lichens. Cyanobacteria are either unicellular species, filamentous species or live in colonial species (Chabili, 2024).

Cyanobacteria have the ability to live in salt-impacted soils like supplement lack, saltiness, and high pH. By accumulating organic solutes, cyanobacteria adapted to salt stress by preserving the level of inorganic ions transport processes' contribution, and different metabolic changes. Numerous researchers have investigated stress-responsive proteins. A limited section of Na^+ is considered to grasp salt-resistant cyanobacteria. Diverse work has been finished to figure out Na^+ efflux .The action of Na^+ - subordinate K^+ Take-up and arrangement of viable solutes and lipids content in cyanobacteria under salt pressure. Improvement of cyanobacterial by combining nitrogen, and salt tolerance can be achieved Investigation of this multitude of systems aids in our understanding of cyanobacteria's salt tolerance (Chabili, 2024).

Cyanobacteria further develop the property of saline soil. Where, the application of cyanobacteria increases the amount of fixed nitrogen in the soil and improves its structure. Improvement, abatement of pH, electrical conductivity, and Na^+. The crop benefited from these changes. yield and productivity in salt-affected soil that is alkaline and has high pH and Na^+ favors the development of cyanobacteria with an ensuing lessening in pH. Cyanobacteria application to saline soil decreases the electrical conductivity (Chabili, 2024).

A cyanobacterium decreases the sodium particle content of the wastewater by making more calcium particles accessible to cyanobacteria. Also, the excreted extracellular polysaccharides can increase soil structure and improve soil structure (Weisenburger, 1993)

It has been reported that the organic matter content was upgraded in saline soil after cyanobacteria application. Furthermore, available phosphorous and sulfur are increased in soil in response to the application of cyanobacteria. The Cyanobacteria integrate in the saline ecosystems and make soil's physical and chemical properties better by adding carbon to, nitrogen, and available phosphorous (Singh, 2016).

2.8. Cyanobacteria and Microalgae as Bio-Control Agents

It is commonly known that the mother of many kinds of secondary metabolites, such as those with antibacterial, antiviral, and antifungal properties, is cyanobacteria (Yadav *et al.*,2022).

Simple and closely related to bacteria, cyanobacteria possess simple forms of life. Their morphology allows them to take on single-celled, filamentous, or colony forms, and they can do photosynthesis like algae. Fig.12. shows the phenotypic examination of cyanobacteria; they lack membrane-bound organelles and a nucleus, similar to chloroplasts. The cyano in "cyanobacteria" is the result of the combination of the green chlorophyll and the blue pigment known as phycocyanin. Because of the pigment phycoerythrin, not all cyanobacteria are blue; others appear red or pink (Mona *et al*., 2020).

Microalgae are unicellular, eukaryotic, photosynthetic microorganisms that primarily inhabit water. Even though cyanobacteria, also referred to as "blue-green algae" are prokaryotic and not true algae, we have included them in this overview since they are similar in physiology and ecology to eukaryotic microalgae and share many biotechnological properties with them (Thoré *et al*., 2023).

There has been a lot of interest in the capacity of certain microalgae to produce high-value compounds with remarkable pharmacological and biological properties for use in chemicals and polymers, fish and animal feed, pollution control, and other industries (Khan *et al.*, 2018).

Two uses for microalgae include CO_2 sequestration and wastewater bioremediation (Alam and Wang,2019). Algae are used by the pharmaceutical industry to produce a variety of goods, including therapeutic proteins, antivirals, antimicrobials, and antifungals (Sathasivam *et al*., 2019).

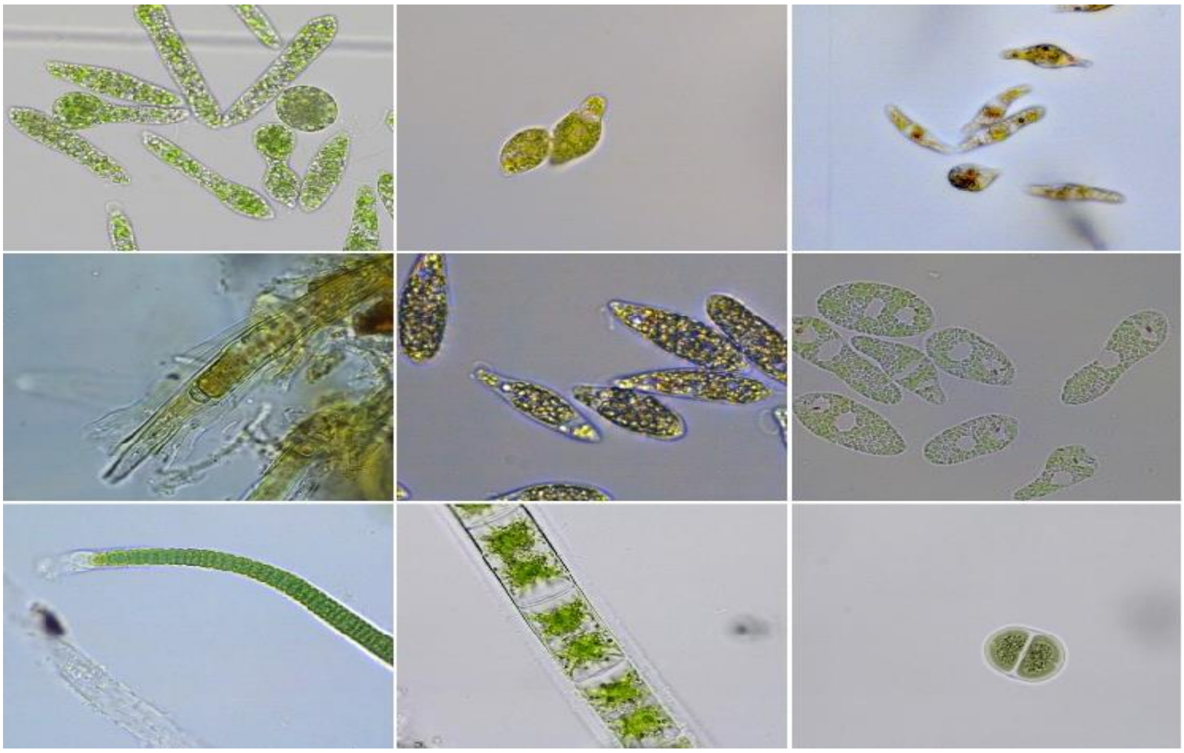

Fig.12. Phenotypic micrograph of some cyanobacteria and microalgae species (Miškovičová and Masojídek, 2023).

The biological qualities of the soil and the state of an ecosystem may deteriorate as a result of planting using excessive amounts of chemical fertilizers (Garcia-Gonzalez and Sommerfeld, 2016).

Therefore, using biologically based organic fertilizers, or biofertilizers, in place of chemical fertilizers makes more sense. Biofertilizers are naturally occurring compounds derived from microorganisms such as bacteria, fungi, and microalgae, or they might be living microorganisms themselves. Biofertilizers are considered a sustainable alternative to chemical or synthetic fertilizers. Applying biofertilizers can improve the soil's chemical and biological properties (Abdel-Raouf *et al.,* 2012).

Applying compost and microalgae-based biofertilizers can improve soil fertility and crop production while lowering the requirement for chemical fertilizers (Abinandan *et al.,* 2019; Alvarez *et al.,* 2021; Chia *et al.,* 2020). The bioactive compounds and secondary metabolites found in microalgae are valuable and promising fertilizer agents that may boost agricultural yields (Kang *et al.,* 2021).

Green microalgae can enhance agricultural output in a number of ways, including: (1) nutrient fertilizer by releasing insoluble or immobile nutrients into the soil, (2) microalgae's biomass photosynthetic potential makes them an enricher of carbon organic matter, (3) catalyst for macro- and micronutrient mineralization processes, which increase soil organic matter and improve soil, and (4) phytohormone producers (gibberellins, auxin, and cytokinin) are recognized to be essential for the growth of plants (Gonçalves, 2021; Kholssi *et al.,* 2019; Ortiz-Moreno *et al.,* 2019).

2.8.1. Cyanobacteria and Microalgae as Biofungicide Agent

Powdery mildew, caused by *Erysiphe betae*, is a serious worldwide hazard to sugar beet plants. The produced sugar's production, quality, and sugar content are all drastically decreased (Kumar *et al.,* 2021). Recently, the microscopic filamentous cyanobacterium *Spirulina platensis* has been proposed as a sustainable, very nutrient-dense, and environmentally benign microalga (Eleiwa *et al.,* 2018).

Spirulina is an effective scavenger of free radicals, strong anti-inflammatory, and able to inhibit the growth of some yeasts, gram-positive and gram-negative bacteria, and *candida albicans* (Marangoni *et al.,* 2017).

Anabaena variabilis is a species of cyanobacterium that has antifungal characteristics that stop plant-pathogenic fungus from growing. In the presence of A. variabilis extracts, two plant-pathogenic fungus strains, *Aspergillus niger* and *Rhizopus stolonifer,* may develop and mature more slowly. The creation of the zone of inhibition demonstrated the substantial antifungal activity of the Anabaena extracts (Tiwari and sharma, 2013).

Moreover, because these three have more antibacterial action, they can effectively lessen the severity of powdery mildew: *Spirulina platensis*, *Nostoc muscorum*, or *Anabaena oryzae* as shown in Fig.13. Cyanobacteria have two types of antifungal properties, the constitutive type in which cyanobacteria such as *S. platensis* and *A. oryzae* emit mostly antifungal compounds, and the induced kind where cyanobacteria create antifungal substances in response to the presence of fungus. The antifungal substances that N. *muscorum generates* to combat *E. betae* are one illustration of this (Kumar *et al.*, 2021).

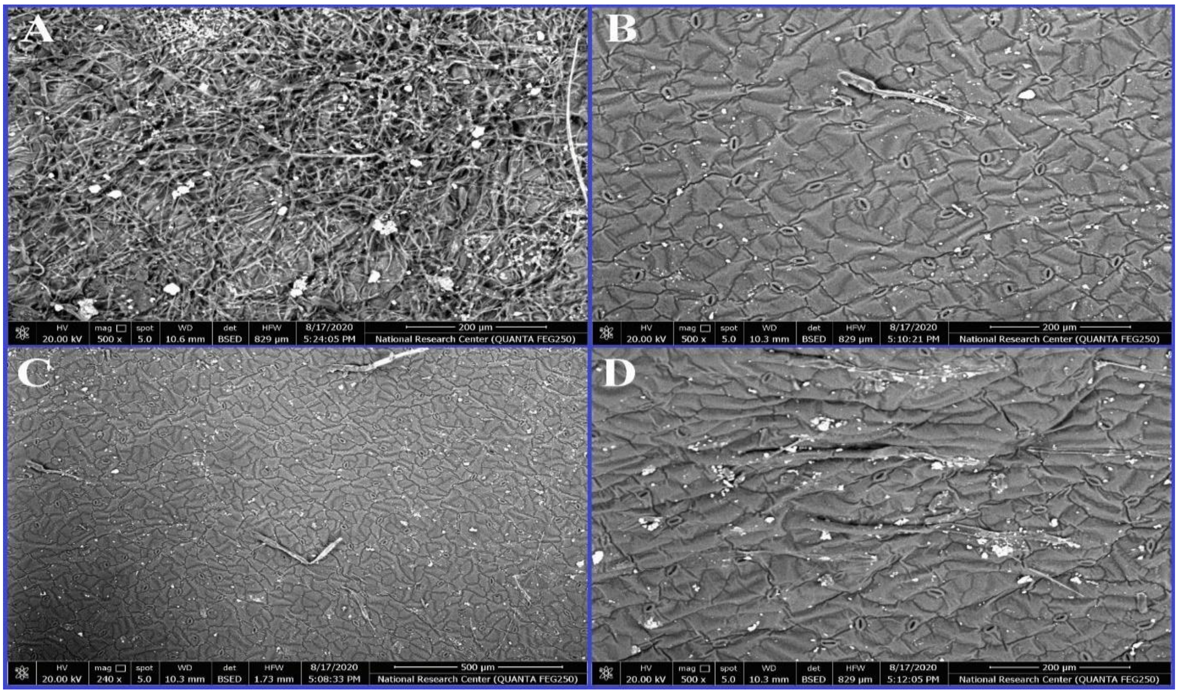

Fig.13. Micrograph of promising foliar treatment on sugar beet, according to scanning electron microscope (SEM) findings, (1) Control, (2) *N. muscorum,* (3) *S. platensis*, and (4) *A. oryzae* (Kumar *et al.*, 2021).

Cyanobacterial extracts have been demonstrated in numerous studies to be effective in the agar medium assay against oomycetes and fungal infections. Research on *Nostocales* and *Oscillatoriales* has been the highest since the early 2000s. Many extracts inhibited *Aspergillus* species, including *Anabaena* spp., *Microcystis aeruginosa, Nostoc* spp.*, Scytonema* spp.*, Lyngbya lutea*, *Oscillatoria* spp.*, Phormidium tenue, Trichodesmium hildebrantii, Synechococcus elongates*, and *Synechocystis* spp. The methanol extract of these cyanobacteria has repeatedly demonstrated fungal inhibition (Marrez and sultan, 2016; Shishido *et al., 2015;* El-Sheekh *et al*., 2006; Pawar and Puranik, 2008).

Fig.14 illustrates the bioactive effect of *Calothrix elenkinii* treated as a biomass culture in a potting mix under controlled conditions, and another *Anabaena* species, *A. laxa*, similarly triggered plant defensive responses, including peroxidases and β-1,3 glucanases, in pathogen-unchallenged coriander, cumin, and fennel plants (Kumar *et al*., 2013).

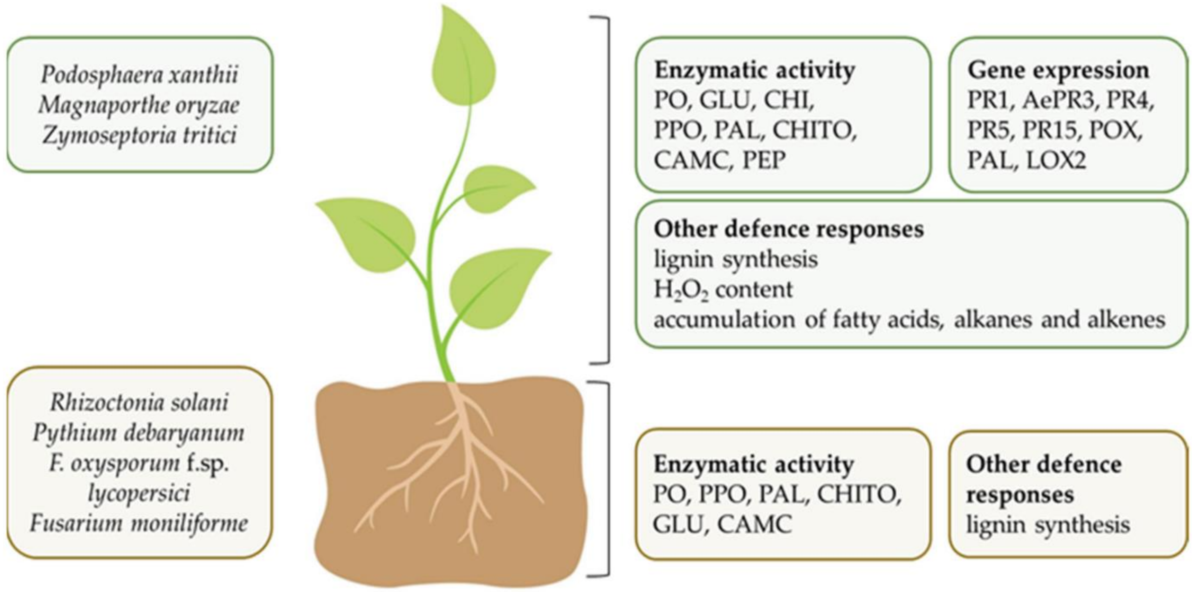

Fig.14. Plant defensive responses in the shoot and root caused by the cyanobacteria described in this research, as well as foliar and soil-borne diseases controlled by cyanobacteria treatment (Kumar *et al.*,2013).

Phosphoenolpyruvate carboxylase (PEP), pathogenesis-related proteins (PR), chitinases (CHIT), chitosanase, GLU, β-1,3-glucanases, LOX, 13-lipoxygenase 2, phenylalanine ammonia lyase, peroxidases (PO), polyphenol oxidases (PPO), and family of transcription factors (WRKY) (Righini *et al*., 2022).

Additionally, an aqueous extract of *Synechocystis* sp., *Oscillatoria* spp., *Phormidium tenue*, and *Lyngbya lutea* was used to manage *Aspergillus* sp. growth (Pawar and Puranik, 2008).

Aspergillus aeruginosa, Calothrix brevissima, Anabaena spp.*, Nodularia* spp.*, Nostoc* spp.*, Lyngbya lutea, Fusarium species* growth reduction was discovered to be caused by *Oscillatoria* spp.*, Phormidium* spp.*, Trichodesmium hildebrantii, Synechococcus elongates,* and *Synechocystis* sp. (Marrez and sultan, 2016; Prasanna *et al*., 2013; Chaudhary *et al*., 2012; Alwathnani and Perveen, 2012 ; Prasanna *et al*., 2008; Pawar and Puranik, 2008; Kim and Kim, 2008; El-Sheekh *et al*., 2006; Kim, 2006; Biondi *et al*., 2004).

More specifically, most cyanobacteria species (*Nostoc* spp.*, Lyngbya lutea; Oscillatoria* spp.*, Phormidium* spp.*, Trichodesmium hildebrantii, Synechococcus elongates*, and *Synechocystis* spp.) had their Fusarium growth successfully reduced (Alwathnani and Perveen, 2012; Pawar and Puranik, 2008; Kim and Kim, 2008; Kim, 2006; Biondi *et al*., 2004).

Extracts prepared with other organic solvents, such as n-propanol, petroleum ether, aceton, methyl chloride, diethyl ether, and ethyl acetate, were likewise successful in eliminating *Fusarium* species (Marrez and sultan, 2016; Pawar and Puranik, 2008).

Furthermore, *Fusarium* spp. growth was suppressed by an aqueous extract from *Phormidium tenue* and culture filtrates from several *Anabaena* sp. Extracted cyanobacteria has been shown to be effective not only against *Aspergillus* and *Fusarium* sp. but also against other plant diseases (Table 5) (Prasanna *et al*., 2013; Chaudhary *et al*., 2012; Pawar and Puranik, 2008).

Table 5: Agar medium experiments evaluating the effectiveness of cyanobacteria extracts and culture filtrates against oomycetes and phytopathogenic fungi (Prasanna *et al.*, 2013; Chaudhary *et al.*, 2012; Gupta *et al.*, 2010).

Cyanobacterium	**Extract/Culture Filtrate 1**	**Plant Pathogen**	**Reference**
Chroococcales ***Microcystis aeruginosa***	Methanol Ethanol	*Aspergillus carbonarius and Aspergillus niger* *Aspergillus flavus, Aspergillus niger and Aspergillus parasiticus*	(Marrez and sultan, 2016)
Nostocales ***Anabaena* spp.** ***Anabaena* sp.**	Culture filtrate Methanol	*Alternaria solani*, *Drechslera oryzae*, *Fusarium moniliforme*, *Macrophomina phaseolina*, *Pythium aphanidermatum* *Aspergillus flavus*	(Prasanna *et al.*,2008) (Shishido *et al.*, 2015)
Oscillatoriales ***Arthrospira platensis*** ***Phormidium autumnale***	Phycobiliproteins Methanol	*Botrytis cinerea* *Fusarium oxysporum f.sp. lycopersici*	(Righini *et al.*, 2020) (Alwathnani and Perveen, 2012)
Synechococcales ***Synechococcus elongates*** ***Synechocystis* sp.**	Water Petroleum Ether	*Colletotrichhum musa* *Colletotrichhum musa*	(Pawar and Puranik, 2008)

2.8.2. Cyanobacteria and Microalgae as Biobactericide Agent

One of the biggest problems in public health today is antimicrobial resistance (AMR). Because of the concerning decline in the effectiveness of antibiotic treatments brought on by microbes developing increased resistance, we are today facing a global antibiotic resistance (AMR) problem (Rojas *et al*., 2020; Aslam *et al*.,2018).

Prokaryotes like cyanobacteria and photosynthetic eukaryotes like microalgae greatly contribute to the richness of these aquatic ecosystems because they are at the base of their food chain (Barzkar *et al*., 2019; Maschek *et al*., 2008).

Extremely high or low pH, salinity, temperature, or hazardous substances are just a few of the challenging environments to which these microorganisms can adapt. They can generate bioactive compounds and defense systems as a result of this trait, which enables them to live in such hostile conditions (Rojas *et al*., 2020; Borowitzka, 2018; Ramos *et al*., 2017; Maschek *et al*., 2008).

The chemical variety of these metabolites and their capacity to actively impede the development of specific tolerant diseases (Barzkar *et al*., 2019).

Protein contents of cyanobacteria and microalgae are generally high, exceeding those of soybean, corn, and wheat. Furthermore, these foods are especially high in polyunsaturated fatty acids, which include ALA, GLA, ARA, EPA, and DHA. Certain microalgae species, such *Nannochloropsis oceanica*, *Chlorella vulgaris*, or *Scenedesmus obliquus*, have lipid concentrations that exceed 20% of their dry weight, despite the fact that growth conditions have a major influence on lipid formation (Kratzer and Murkovic, 2021).

Studies have demonstrated that the substance known as chlorellin can impede the growth of bacteria that are Gram-positive (*Bacillus subtilis*, *S aureus*, and *S.epidermidis*) in addition to Gram-negative bacteria (*Pseudomonas* and *Escherichia coli*). (Falaise *et al*., 2016; Pratt *et al*., 1944).

600 strains of microalgae and cyanobacteria were selected from the Coimbra Collection of Algae (ACOI) and the Blue Biotechnology and

Ecotoxicology Culture Collection (LEGE-CC) after the antibiotic and antibiofilm activities of total cellular extracts were screened for the NoMorFilm H2020 project. The extracts from freeze-dried biomasses were extracted using hexane, ethyl acetate, and methanol in that order (Cepas *et al*., 2019).

These strains were members of the following phyla: *Euglenophyta, Glaucophyta*, *Haptophyta*, *Miozoa*, *Ochrophyta*, *Rhodophyta*, *Cryptophyta*, *Charophyta*, and two unidentified species. These extracts' antibiofilm and antibacterial properties were assessed against strains of Coagulase-negative Staphylococcus (CoNS), *S. aureus, S. epidermidis, K. pneumoniae, E. cloacae, P. aeruginosa, E. coli, C. parapsilosis*, and *C. albicans*. The extracts that demonstrated both properties were then investigated further (Cepas *et al*., 2019).

It is known that these microorganisms may survive in a variety of environments, such as freshwater, saltwater, and terrestrial settings. In addition, a variety of predators as well as microbial pathogens, such as bacteria, viruses, and fungus, are known to be susceptible to them (Table 6). Their variable metabolism enables them to respond to different environmental challenges and nutrition sources, as well as to adapt to different growth conditions and habitats. Their flexibility explains the range and volume of chemical substances that have been extracted from them (Shah *et al*., 2017; Falaise *et al*., 2016).

Table 6: Bioactive biochemical compounds produced by cyanobacteria that have antibacterial properties.

Cyanobacterial Species	Class of Compound	Reference
Fischrella sp. *Fischrella ambigua* *Nostoc sp.* *Nostoc spongiaeforme*	Alkaloids Eucapsitrione Nostocarboline Tjipanazole A and D Nostocine A	(Swain et al., 2017 Singh et al., 2017; Senhorinho et al., 2015; Nagarajan et al., 2013; Singh et al., 2011; Olk and Furkert et al., 2006)
Fischrella ambigua	Aromatic compounds Ambigol A and B	(Swain *et al.*, 2017; Singh *et al.*, 2017; Nagarajan *et al.*, 2013; Moore *et al.*,1996).
Nostoc sp.	Cyclophanes Carbamidocyclophane A–E Nostocyclyne	(Swain et al., 2017; Singh et al., 2017; Senhorinho et al., 2015; Singh et al., 2011).
Moorea producens *(L. majuscula)*	Dicarboximides Malyngamide C, I and J	(Dussault et al., 2016).
Fischerella sp. *Spirulina platensis* *Phaeodactylum tricornutum* *Oscillatoria redekei* *Scytonema* sp. *Scytoscalaro*	Fatty Acids and Lipids Colioric acid α-dimorphecolic acid γ-linolenic acid	(Bashir *et al.*, 2018; Singh *et al.*, 2017; Senhorinho *et al., 2015;* Pradhan *et al.*, 2014; Nagarajan *et al.*, 2013; Burja *et al.*, 2001).
Lyngbya majuscula	Lactones δ-lactone malyngolide	(Singh *et al.*, 2017)
	Macrolides	

Scytonema sp.	Scytophycin A and C Tolytoxin	(Swain *et al*., 2017).
Nostoc sp.	Paracyclophanes	(Nagarajan *et al*., 2013)
Dunaliella salina	Indolic Derivatives β-ionone Neophytadiene	(Falaise *et al*., 2016; Senhorinho *et al*., 2015; Amaro *et al*., 2011).
Chlorella vulgaris *Chlorella pyrenoidosa* *Chaetoceros muelleri* *Chlorococcum* sp. *Dunaliella salina* *Dunaliella primolecta* *Haematococcus pluvialis* *Navicula delognei* *Phaeodactylum tricornutum* *Planktochlorella nurekis* *Scenedesmus obliquus* *Skeletonema costatum*	Fatty Acids and Lipids Chlorellin Butanoic acid Docosa-pentaenoic acid (DPA) Eicosapentaenoic acid (EPA) Hexadecatrienoic acid (HTA) α-linolenic acid (ALA	(Singh *et al*., 2017; Falaise *et al*., 2016; Shannon and Abu-Ghannam, 2016; Senhorinho *et al*., 2015; Pradhan *et al*., 2014; Amaro *et al*., 2011; Santoyo *et al*., 2009; Pratt *et al*., 1944).
Amphidinium sp.	Macrolides Amphidinolide Q	(Kubota *et al*., 2014).
Isochrysis galbana	Pigments Carotenoids Chlorophyll a derivatives (Pheophytin a and chlorophyllide a) Phycobiliproteins	(Falaise *et al*., 2016; Senhorinho *et al*., 2015; Pradhan *et al*., 2014; Amaro *et al*., 2011).

Isochrysis galbana (six classes)	Terpenoids Diterpenoids	(Amaro *et al*., 2011; Duff *et al*., 1966).

2.8.3. Cyanobacteria and Microalgae as Biopesticide Agent

In agricultural production, biochemical pesticides are used to control pests through non-toxic means; nevertheless, excessive applications of fertilizers or pesticides can poison weeds and cause a range of development irregularities, such as limiting root growth and carbon assimilation. The microtubule system and membrane deterioration are the direct causes of weed death (Mfarrej and Rara, 2019). The reckless use of synthetic pesticides and fertilizers has been seriously harming the environment, human and animal health, and the ecosystem for decades. These include the decrease in soil fertility, the increase in the solubility of dangerous heavy metals, and the advent of new diseases that kill crops and cause enormous costs to the world economy (Kumar and Verma, 2013; Raymaekers *et al.*, 2020).

Consequently, the development of microbial pesticides utilizing organic components like bacteria, fungi, or algae has become imperative. It is believed that cyanobacteria are one of the main biological agents that control dangerous fungi in plants and soil ailments (Stavi and Lal, 2015). They produce bioactive compounds called secondary metabolites, which have antibacterial and antifungal qualities and are toxic to worms (Marks *et al.,* 2019; Mager and Thomas, 2011).

Microalgae and cyanobacteria produce a variety of metabolites as a result of their biological activity, which can be used in agriculture as fertilizers, biostimulants, or biopesticides (Fig.15). It has previously been discovered that these metabolites, which include carotenoids, polysaccharides, terpenoids, FFAs, phenolic compounds, and phytohormones, stimulate plant growth (Singh *et al*., 2017; Pan *et al*., 2019; Kusvuran *et al*., 2019).

Inducing materials produced by microalgae include biomass and chemicals that can be used to create biopesticides, which enhances crop protection. Wastewater has a lot of nitrogen, phosphorus, carbon, and ammonium, all of which are necessary for the growth of microalgae, therefore it can be utilized to produce them. Chlorella vulgaris is often used in wastewater treatment because to its remarkably high resistance to ammonium (Ranglová *et al*.,2021).

Single-celled green algae such as *Nostoc piscinale*, *Chlamydopodium fusiforme*, and *Chlorella vulgaris* are examples of filamentous cyanobacterium sources of biopesticides (Ranglová *et al*.,2021).

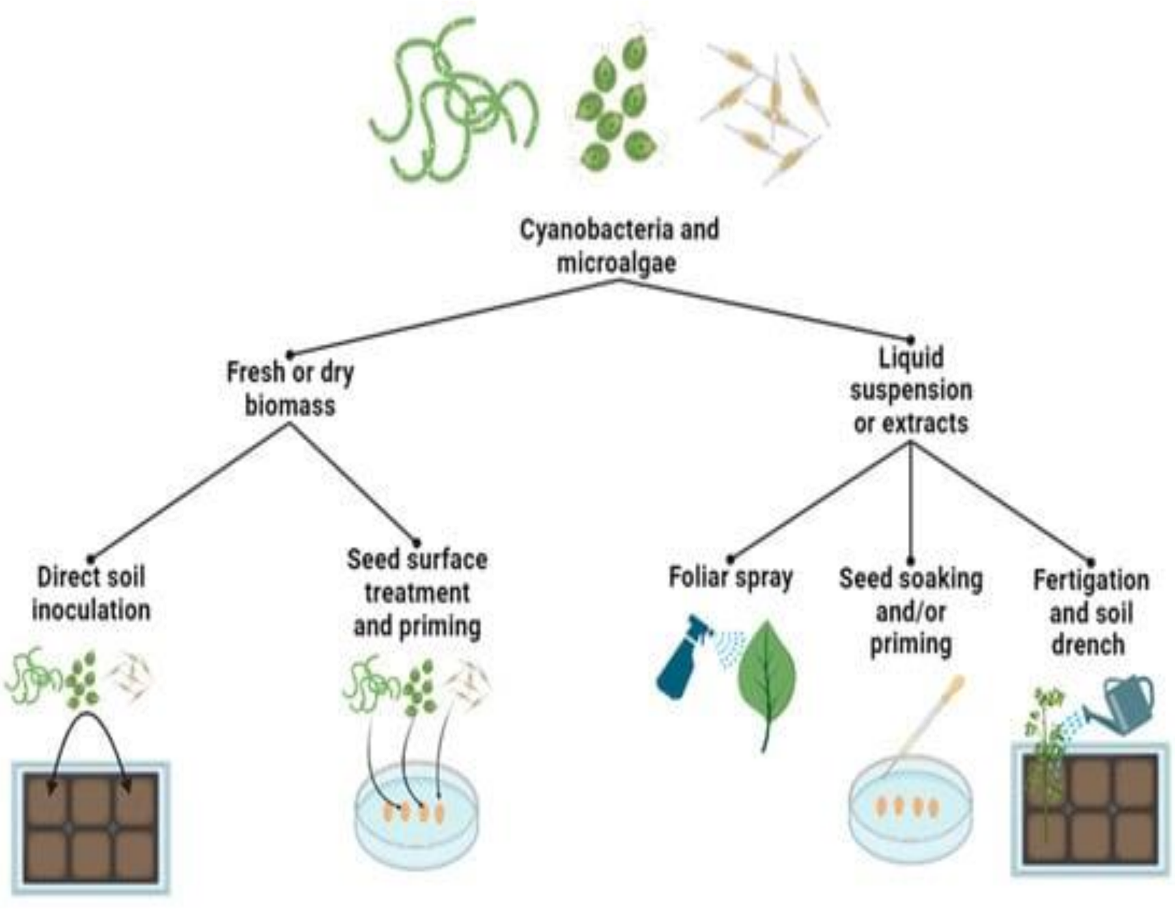

Fig.15. Microalgae and cyanobacteria-based biostimulant application methods (Chabili *et al*.,2024).

The production of stimulating materials by microalgae, such as biomass and chemicals that can be used to create biopesticides, enhances crop protection

(Table 7). Wastewater has a lot of nitrogen, phosphorus, carbon, and ammonium, all of which are necessary for the growth of microalgae, therefore it can be utilized to produce them. *Chlorella vulgaris* is often used in wastewater treatment because of its remarkably high resistance to ammonium (Ranglová *et al.*, 2021).

Filamentous cyanobacterium (single-celled green algae) such as *Nostoc piscinale*, *Chlamydopodium fusiforme*, and *Chlorella vulgaris* are examples of microalgal source biopesticides (Ranglová *et al.*,2021).

Additionally, two examples of organisms that aid in enhancing fungicidal action are *Anabaena laxa* and *Calothrix elenkinii*, which attack crops like fennel, cumin, and coriander (Kumar *et al.*,2013).

Table 7: Biologically active compounds produced by cyanobacteria and microalgae that may have multiple application in agricultural technology

Metabolites	**Examples**	**Cyanobacterial and Microalgal Sources**	**Biological activity**	**Role in Agriculture**	**References**
Terpenoids	Monoterpenes, diterpenes, triterpenes, polyterpenes	*Phlocamium cornutum*, *Plocamium leptophyllum*, *Portieria hornemann*	Antioxidant, antibacterial	Stimulation of plant development and early growth	(Wei *et al*., 2019; Betterle and Melis, 2019) (Pan *et al*., 2019 ;Awasthi *et al*.,2018;Singh *et al*., 2017; Rodríguez-García *et al*., 2017) (Pavela et al.,2016; Pattanaik *et al*.,2015; Gershenzon and Dudareva, 2007)
Free Acids	Fatty acids, both saturated and unsaturated	*Porphyridium*, *Scenedesmus*, *Spirulina*, *Anabaena*	Antibiotic, antiviral, antifungal, anticarcinogen, and antioxidant	Protection of crops from diseases and biotic and abiotic stress factors	(Pan *et al*., 2019; Feller *et al*.,2018; Singh *et al*., 2017; El-Baz *et al*.,2013; Lam and Lee, 2012; Demirbas and Demirbas, 2011; Descois and Smith, 2010).
Polysaccharide	Energy storing polysaccharides, extracellular polysaccharides	*Arthrospira*, *Chlamydomonas* ,*Chlorella*, *Cylindrotheca*,	Antimicrobial anticoagulant, anticancer, anti-inflammatory	Enhancement soil conditions and Promotion of plant growth	(Chanda *et al*., 2019; Pan *et al*., 2019; El Arroussi *et al*., 2018; Farid *et al*.,2019; Singh *et al*., 2017; Usman *et al*.,2017; Delattre *et al*.,2016; Elarroussia *et al*.,2016; Campos *et*

					al.,2015; Guilherme *et al*.,2015; González *et al*., 2013; Vera *et al*.,2011; Dvir *et al*.,2009; Rechter *et al*.,2006; Guzmán *et al*.,2003)
Carotenoids	Alpha-carotene; beta-carotene; lutein; lycopene; astaxanthin; zeaxanthin	*Phaeodactylum tricornutum, Haematococcus pluvialis*	Antioxidant, anti-inflammatory, and anti-cancer	crops fortification, and soil bioremediation and fertilization	(Pan *et al*., 2019; Cezare-Gomes *et al*., 2019; Galasso *et al*., 2017; Rajesh *et al*., 2017; Sakamoto *et al*., 2017; Han *et al*., 2016; Raposo *et al*.,2015; Guedes *et al*., 2011)
Phytohormones	Auxins; abscisic acid; cytokinin; ethylene; gibberellins	Arthrospira, Protococcus, Scenedesmus, Phormidium	Chemical messengers	Stimulation of plant growth, control over crop cellular activity	(Ronga *et al*.,2019; Pan *et al*.,2019; Han *et al*.,2018; Singh *et al*., 2017; Lu *et al*.,2015; Ördög *et al*.,2004)
Phenolic compounds	Phenylpropanoids, phenolic acids, and polyphenols	*Odontella sinensis, Phaeodactylum tricornutum, Chlorella vulgari*	Antifungal, antibacterial, and antioxidant	Protection of crops from diseases and biotic and abiotic stress factors	(Pan *et al*., 2019;Singh *et al*., 2017; Esquivel-Hernández *et al*.,2017; Foo *et al*., 2017;Michalak *et al*.,2017; Khoddami *et al*.,2013; Goiris *et al*.,2012; Oksana, 2012)

2.9. Microalgae and Cyanobacteria Forms in Improving Grain Yield and Yield Components

Maintaining high levels of agricultural output while both lowering environmental effects and promoting environmental regeneration is a pressing concern. Microalgae are useful in addressing this challenging agricultural environment because of their many unique qualities. Microalgae enhance soil fertility, support plant development and protection, and provide a substitute for chemical fertilizers and pesticides in agricultural contexts (Alvarez *et al.*, 2021).

Algae provide almost half of the photosynthetic production on Earth. Microalgae are a versatile potential resource for agriculture. Unlike conventional chemical fertilizers, microalgae supply organic carbon (C) to the soil when they are introduced. This is a factor that is becoming more significant because soil organic C depletion is one of the primary types of degradation in croplands that leads to declining soil quality and fertility (Alvarez *et al.*, 2021).

In addition, microalgae generate bioactive compounds that influence plant development and control pests and diseases. Furthermore, the biomass from algae can break down and transform into nutrients that plants can use. The biomass, activity, diversity, and composition of the communities all affect the microbial populations in the soil. Apart from providing nutrients and triggering protective reactions in plants, cyanobacteria can also fix atmospheric nitrogen (N_2) and adhere to the roots of plants as shown in Fig.16 (Alvarez *et al.*, 2021).

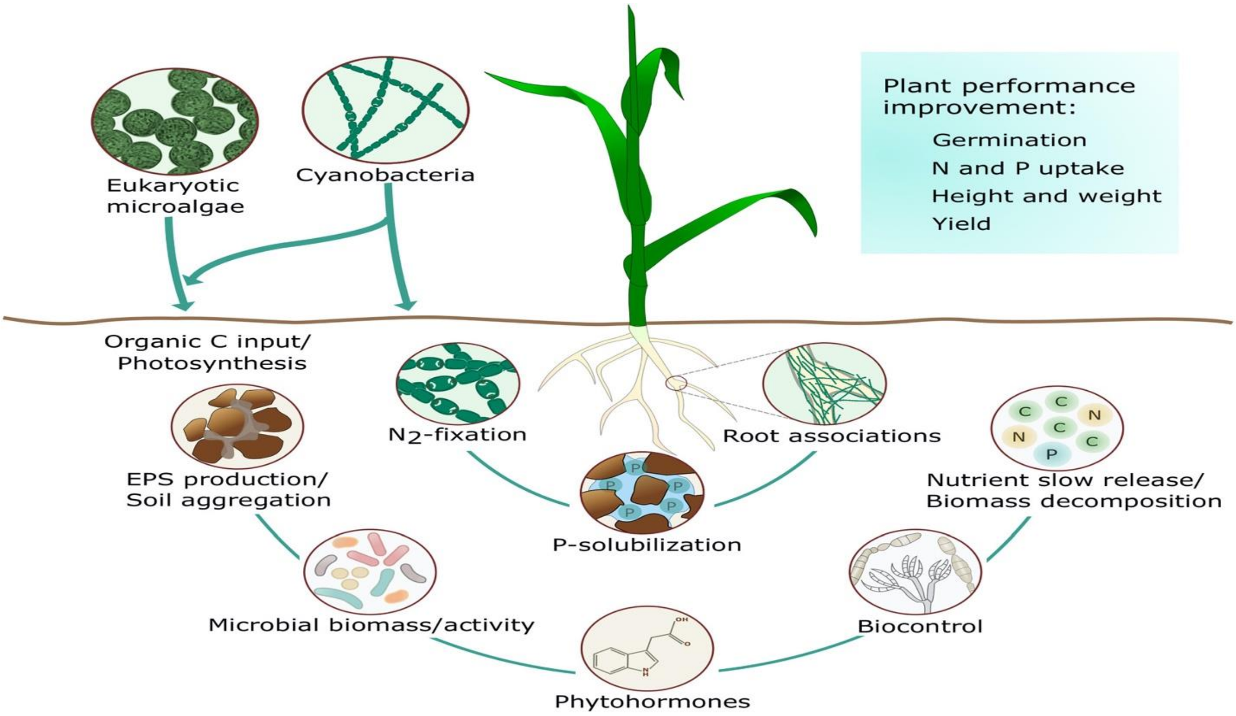

Fig.16. Representative diagram showing some of beneficial effects of microalgae and cyanobacteria to plants and soil health (Alvarez *et al.*, 2021).

Microalgae can be used to produce a range of agricultural products that could be used for crop protection, soil enhancement, and crop production because of the diverse effects that microalgal biomass, also known as microalgal compounds, have on plants and soils represented in Fig.17 (Alvarez *et al.*, 2021). Adding microalgal biomass to soil as a micro-algal soil supplement can improve physical properties like soil structure and water retention. One potential application for microalgal biomass is as a soil conditioner (Alvarez *et al.*, 2021). Additionally, whether applied to soil, seeds, or plant surfaces, microalgae can be utilized as biofertilizers, or microbial inoculants that promote plant growth by increasing the supply or availability of nutrients to the plant through the action of live microorganisms (Alvarez *et al.*, 2021).

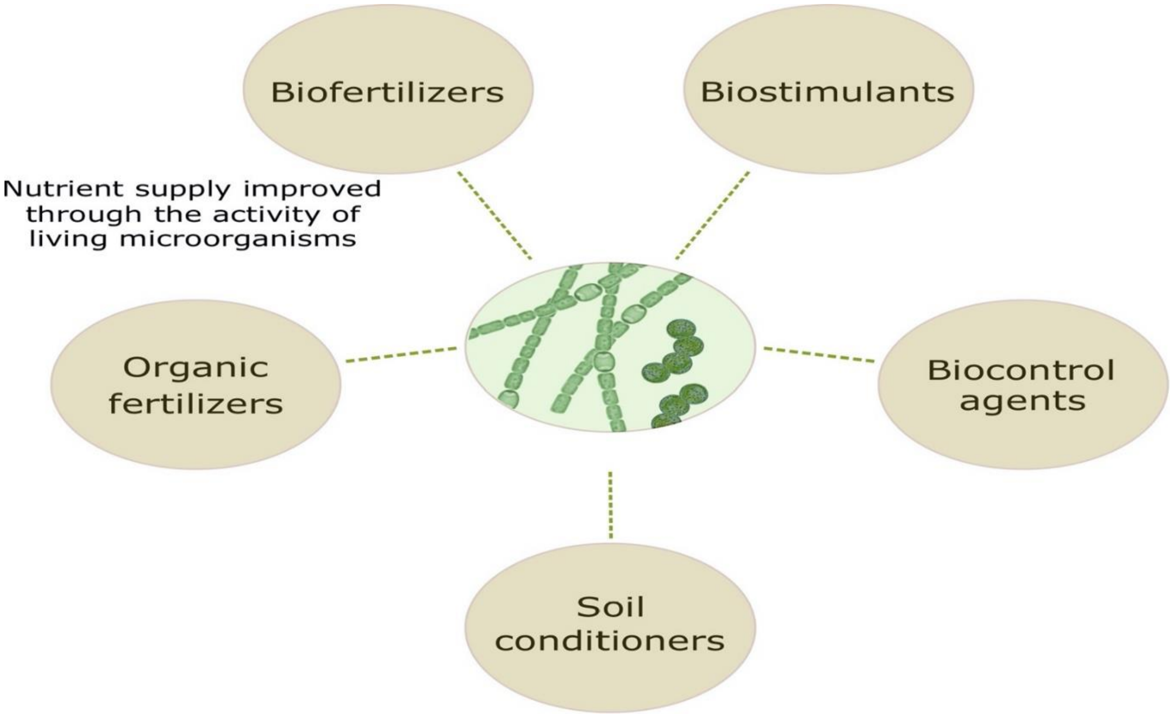

Fig. 17. Potential products made from agricultural microalgae that could enhance soil quality and protect and produce crops (Alvarez *et al.*, 2021).

Active microalgae-derived biofertilizers can improve the soil's microbial ecosystem, plant development, nutrient utilization efficiency, simultaneous resistance to abiotic stress, and the use of chemical fertilizers (Yoder and Davis *et al*., 2020; Ronga *et al*., 2019). During growth, the contents of internal and extracellular polysaccharides in certain microalgae species can significantly rise, fixing more carbon in the soil and increasing total carbon (TC) and dissolved organic carbon (DOC) (Jiajun *et al*.,2019).

To boost soil nitrogenase activity, biostimulants made from microalgae can be applied either by themselves or in conjunction with traditional biological fertilizers (Cai *et al*., 2017). Because of the valuable benefits that microalgal biomass has on soil and plants, using microalgae in crop production would be supported (Alvarez *et al*., 2021).

2.10. Role of Microalgae and Cyanobacteria in Heavy Metals Removal

Heavy metals including lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), mercury (Cr), and others even in minute concentrations can be harmful and cause cancer. Because of bioaccumulation brought on by their persistence in the food chain, human health and environmental ecology are at risk. Microalgae have become more and more popular as a heavy metal cleanup method due to its high removal efficacy, cost, and convenience of usage. Microalgae's speedy development, ease of usage, and non-toxic approach are also their main advantages over higher plants (Leong and Chang, 2020).

In addition to generating free radicals against heavy metals, the adsorption process of microalgae generates antioxidants such as glutathione reductase, superoxide dismutase (SOD), peroxidase, ascorbate peroxidase, catalase, and others (Upadhyay *et al.*, 2016).

Specifically, the two-stage biosorption and bioaccumulation strategy that microalgae employ to eliminate heavy metals are show in Fig.18. Whereas biosorption is the rapid passive adsorption outside the cell, bioaccumulation is a slow, active transport process. Different functional groups present in the microalgal cell wall allow them to bind heavy metals. These groups include lipids, organic proteins, polysaccharides, and cellular macromolecules such peptides and exopolysaccharides (Priatni *et al.*, 2016).

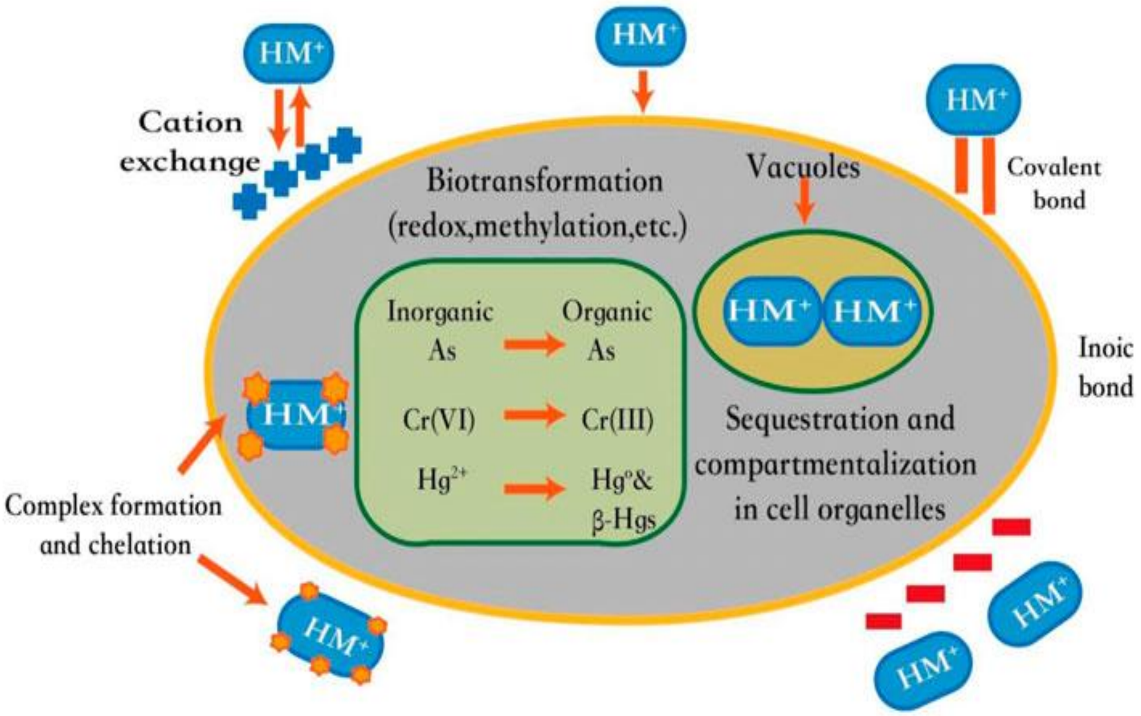

Fig.18. Mechanism by Which Microalgae Remove Heavy Metals (Leong and Chang, 2020).

Malathion, an organophosphorus pesticide, was discovered to impede the growth of *Aspergillus oryzae* and *Nostoc muscorum* in crop fields; nevertheless, malathion could be broken down and utilized as a source of phosphorus by nitrogen-fixing cyanobacteria (Ibrahim *et al*.,2014).

Of all of them, *Candida grisea* has the highest biodegradability (91%). It was found that anabaena isolated from rice fields could survive polychlorinated biphenyls (PCBs) (Hangjun *et al*.,2015). It was found that the extract from *Scytonema* sp. could degrade methyl parathion and subsequently use the leftover phosphorus (Tiwari *et al*., 2017).

Microbes produce substances called antibiotics during metabolism that, in small quantities, can prevent other bacteria from proliferating and acting (Sherpa *et al*., 2015).

Antibiotics are widely used in soil science, aquaculture, and agricultural planting (Chuah *et al*., 2016). It has been discovered that antibiotics have a strong influence on keeping bacteriostasis and inhibiting aquatic bacteria from proliferating and self-sanitizing (Lijian *et al*.,2020).

It is normal to add different types of antibiotics to the algal fluid to achieve bacteriostasis, or sterilization. Different antibiotic treatments can also be used at different phases of microalgae growth. When eight different antibiotics were used to sterilize *Haematococcus pluvialis*, the antibacterial effect of adding griseofulvin in the early stages was the most effective; however, the antibacterial effect of adding penicillin in the middle and late stages was more noticeable (Kiki *et al*., 2020).

During the microalgal culture process, antibiotics are employed to block bacteria from developing, but they also have an impact on the pace of growth, algal cell density, and chlorophyll content (Shan *et al*., 2020; Dantas *et al*.,2019). Microalgae infiltrate contaminated soil by means of biosorption, bioaccumulation, and breakdown processes. Soil fertility is restored as a result of this degrading process. Aseptic microalgal culture is essential for studies related to genetics, biochemistry, physiology, and taxonomy (Ananthi *et al*., 2018).

The fact that antibiotics stop bacterial growth and reproduction has an effect on sterilization (Xi-aoyu *et al*., 2022) Because microalgae are more resistant to antibiotics than bacteria, sterile algae can be created by carefully selecting and aseptically treating them with one or more antibiotics (Sandhya and Vijayan, 2019).

Cyanobacteria have a major role in saline soil regeneration. They can help cheat harmful sodium ions and raise the nitrogen content of the soil (Kumar *et al.*,2018). Soil health is an important component of the ecological environment. Soil pollution immediately endangers human health and food safety by reducing the quality and productivity of arable land. Photosynthetic microalgae can improve soil physicochemical properties, the composition of the soil microbial community, and recycling because of their many active chemicals. Similarly, a variety of contaminants and underlying factors that lead to soil degradation, such as heavy metals, pesticides, antibiotics, and microplastics, can be controlled by microalgae due to their distinct cell structure or functional group (Song *et al*., 2022).

Overall microalgae and cyanobacteria have a multifunctional benefit on crop yield and yield components either directly on plant or indirectly on improving soil health and upgrading soil microflora.

Conclusion and Recommendation

Conclusion

The recent development in using microalgae and cyanobacteria in the agricultural field has been proved as promising and useful strategy. Beyond their application as biostimulants and soil conditioner, they also provide other multi-functional options including biocontrol of plant diseases and decreasing use of chemical fertilizer. Microalgae or cyanobacterial extracts are rich source of metabolites and growth regulators, making them valuable resource for enhancing crop production. The effectiveness of cyanobacteria and microalgae in maintaining soil crust and providing rhizosphere with needed organic matter and nitrogen content has gained much attention by many researchers. Moreover, salt-tolerant species have been used to reclaim salt-affected soils. These microorganisms have been proposed to solve sum of serious environmental issues (e.g. CO_2 mitigation, heavy metal removal and agrochemical degradation). This review aims to discuss how cyanobacteria and microalgae can be used to enhance soil fertility and promote plant growth in a sustainable and efficient manner.

Recommendation

Due to the increasing demands on food resources, expanding agricultural practices is seen as optimistic solution. Thus, to increase crop yields, mitigate deterioration of the environment and to increase sustainability, the application of microalgae and cyanobacteria in the agricultural practices should be taken into consideration. These microorganisms are not only eco-friendly additives but also have multi-functional options for modern agricultural technologies.

More studies are still needed to understand the interaction between cyanobacteria and microalgae with plant and the environment. Also, more research is still needed in attempt to understand the effect of their metabolites on soil and how these microorganisms influence plant and microbial biodiversity.

References

Abdel-Raouf N. (2012). Agricultural importance of algae. *African Journal of Biotechnology*, *11*(54), 11648– 11658.

Abdel-Razek, M. A., Abozeid, A. M., Eltholth, M. M., Abouelenien, F. A., El-Midany, S. A., Moustafa, N. Y., and Mohamed, R. A. (2019). Bioremediation of a pesticide and selected heavy metals in wastewater from various sources using a consortium of microalgae and cyanobacteria.

Abinandan, S., Subashchandrabose, S. R., Venkateswarlu, K., and Megharaj, M. (2019). Soil microalgae and cyanobacteria: the biotechnological potential in the maintenance of soil fertility and health. *Critical Reviews in Biotechnology*, *39*(8), 981– 998.

Adams, D. G., Bergman, B. I. R. G. I. T. T. A., Nierzwicki-Bauer, S. A., Rai, A. N., and Schüßler, A. (2006). Cyanobacterial-plant symbioses. The prokaryotes: a handbook on the biology of bacteria, 1, 331-363.

Aksu, Z., and Tezer, S. (2005). Biosorption of reactive dyes on the green alga Chlorella vulgaris. Process Biochemistry, 40(3-4), 1347-1361.

Aktar, M. W., Sengupta, D., and Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. Interdisciplinary Toxicology, 2(1), 1-12

Alam, M. A., and Wang, Z. (Eds.). (2019). *Microalgae biotechnology for development of biofuel and wastewater treatment* (pp. 1–655). New York, NY: Springer.

Alori, E. T., Fawole, O., and Afolayan, A. (2012). Characterization of arbuscular mycorrhizal spores isolated from Southern Guinea Savanna of Nigeria. *Journal of Agricultural Science; Vol. 4, No. 7; 2012*, *4*(7), 13-19.

Alvarez, A. L., Weyers, S. L., Goemann, H. M., Peyton, B. M., and Gardner, R. D. (2021). Microalgae, soil and plants: A critical review of microalgae as renewable resources for agriculture. *Algal Research*, *54*, 102200.

Alvarez, A. L., Weyers, S. L., Goemann, H. M., Peyton, B. M., and Gardner, R. D. (2021). Microalgae, soil and plants: A critical review of microalgae as renewable resources for agriculture. Algal Res. 54.

Alwathnani, H. A., and Perveen, K. (2012). Biological control of fusarium wilt of tomato by antagonist fungi and cyanobacteria. *African Journal of Biotechnology*, *11*(5), 1100-1105.

Amaro, H.; Guedes, A.; Malcata, F. Antimicrobial activities of microalgae: An invited review. In *Science against Microbial Pathogens: Communicating*

Current Research and Technological Advances; Méndez-Vilas, A., Ed.; Formatex Research Center: Badajoz, Spain, 2011; pp. 1272–1280. ISBN 84939843.

Ananthi, V., Prakash, G. S., Rasu, K. M., Gangadevi, K., Boobalan, T., Raja, R., et al. (2018). Comparison of integrated sustainable biodiesel and antibacterial nano silver production by microalgal and yeast isolates. J. Photochem. Photobiol. B Biol.

Arun, J., Shreekanth, S. J., Sahana, R., Raghavi, M. S., Gopinath, K. P., and Gnanaprakash, D. (2017). Studies on influence of process parameters on hydrothermal catalytic liquefaction of microalgae (Chlorella vulgaris) biomass grown in wastewater. Bioresource technology, 244, 963-968.

Aslam, B.; Wang, W.; Arshad, M.I.; Khurshid, M.; Muzammil, S.; Rasool, M.H.; Nisar, M.A.; Alvi, R.F.; Aslam, M.A.; Qamar, M.U.; et al. Antibiotic resistance: A rundown of a global crisis. *Infect. Drug Resist.* 2018, *11*, 1645–1658.

Awasthi, M., Upadhyay, A. K., Singh, S., Pandey, V. P., and Dwivedi, U. N. (2018). Terpenoids as promising therapeutic molecules against Alzheimer's disease: amyloid beta-and acetylcholinesterase-directed pharmacokinetic and molecular docking analyses. *Molecular Simulation*, *44*(1), 1-11.

Azziz, G., Bajsa, N., Haghjou, T., Taulé, C., Valverde, Á., Igual, J. M., and Arias, A. (2012). Abundance, diversity and prospecting of culturable phosphate solubilizing bacteria on soils under crop–pasture rotations in a no-tillage regime in Uruguay. *Applied Soil Ecology*, *61*, 320-326.

Babalola, O. O., and Glick, B. R. (2012a). Indigenous African agriculture and plant associated microbes: current practice and future transgenic prospects. *Sci. Res. Essays*, *7*(28), 2431-2439

Babalola, O. O., and Glick, B. R. (2012b). The use of microbial inoculants in African agriculture: current practice and future prospects. *J. Food Agric. Environ*, *10*(3and4), 540-549.

Barzkar, N., Jahromi, S. T., Poorsaheli, H. B., and Vianello, F. (2019). Metabolites from marine microorganisms, micro, and macroalgae: Immense scope for pharmacology. *Marine drugs*, *17*(8), 464.

Bashir, K. M. I., Lee, J. H., Petermann, M. J., Shah, A. A., Jeong, S. J., Kim, M. S., ... and Cho, M. G. (2018). Estimation of antibacterial properties of chlorophyta, rhodophyta and haptophyta microalgae species. *Microbiology and Biotechnology Letters*, *46*(3), 225-233.

Baweja, P., Kumar, S., and Kumar, G. (2019). Organic fertilizer from algae: a novel approach towards sustainable agriculture. *Biofertilizers for sustainable agriculture and environment*, 353-370.

Belnap, J., Weber, B., and Büdel, B. (2016). *Biological soil crusts as an organizing principle in drylands* (pp. 3-13). Springer International Publishing.

Betterle, N., and Melis, A. (2019). Photosynthetic generation of heterologous terpenoids in cyanobacteria. *Biotechnology and bioengineering*, *116*(8), 2041-2051.

Bi, Q. F., Zheng, B. X., Lin, X. Y., Li, K. J., Liu, X. P., Hao, X. L., ... and Zhu, Y. G. (2018). The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. *Chemical Geology*, *483*, 56-64.

Bidyarani, N., Prasanna, R., Babu, S., Hossain, F., and Saxena, A. K. (2016). Enhancement of plant growth and yields in Chickpea (Cicer arietinum L.) through novel cyanobacterial and biofilmed inoculants. Microbiological Research, 188, 97-105.

Bilad, M. R., Discart, V., Vandamme, D., Foubert, I., Muylaert, K., and Vankelecom, I. F. (2014). Coupled cultivation and pre-harvesting of microalgae in a membrane photobioreactor (MPBR). Bioresource technology, 155, 410-417.

Biondi, N., Piccardi, R., Margheri, M. C., Rodolfi, L., Smith, G. D., and Tredici, M. R. (2004). Evaluation of Nostoc strain ATCC 53789 as a potential source of natural pesticides. *Applied and environmental microbiology*, *70*(6), 3313-3320.

Bispo, R. L. B., Ceccato-Antonini, S. R., Takita, M. A., and Rosa-Magri, M. M. (2023). Exogenous indole-3-acetic acid production and phosphate solubilization by Chlorella vulgaris Beijerinck in heterotrophic conditions. *Fermentation*, *9*(2), 116.

Borowitzka, M. A. (2013). High-value products from microalgae—their development and commercialisation. *Journal of applied phycology*, *25*, 743-756.

Borowitzka, M. A. (2018). Microalgae in medicine and human health: A historical perspective. In *Microalgae in health and disease prevention* (pp. 195-210). Academic Press.

Büdel, B., Dulić, T., Darienko, T., Rybalka, N., and Friedl, T. (2016). Cyanobacteria and algae of biological soil crusts. *Biological soil crusts: an organizing principle in drylands*, 55-80.

Burja, A. M., Banaigs, B., Abou-Mansour, E., Burgess, J. G., and Wright, P. C. (2001). Marine cyanobacteria—a prolific source of natural products. *Tetrahedron*, *57*(46), 9347-9377.

Cáceres, T., Megharaj, M., and Naidu, R. (2008). Toxicity and transformation of fenamiphos and its metabolites by two micro algae Pseudokirchneriella subcapitata and Chlorococcum sp. *Science of the total environment*, *398*(1-3), 53-59.

Cai, X., Liu, W., Jin, M., and Lin, K. (2007). Relation of diclofop-methyl toxicity and degradation in algae cultures. *Environmental Toxicology and Chemistry: An International Journal*, *26*(5), 970-975.

Cai, Z., Xiaohua, C., Jiangtao, W., and Liju, T. (2017). Toxic effects of microplastic on marine microalgae skeletonema costatum: Interactions between microplastic and algae. Environ. Pollut. 220, 1282–1288.

Campos, E. V. R., de Oliveira, J. L., Fraceto, L. F., and Singh, B. (2015). Polysaccharides as safer release systems for agrochemicals. *Agronomy for sustainable development*, *35*, 47-66.

Cepas, V., López, Y., Gabasa, Y., Martins, C. B., Ferreira, J. D., Correia, M. J., ... and Soto, S. M. (2019). Inhibition of bacterial and fungal biofilm formation by 675 extracts from microalgae and cyanobacteria. *Antibiotics*, *8*(2), 77.

Cezare-Gomes, E. A., Mejia-da-Silva, L. D. C., Pérez-Mora, L. S., Matsudo, M. C., Ferreira-Camargo, L. S., Singh, A. K., and de Carvalho, J. C. M. (2019). Potential of microalgae carotenoids for industrial application. *Applied biochemistry and biotechnology*, *188*, 602-634.

Chabili, A., Minaoui, F., Hakkoum, Z., Douma, M., Meddich, A., and Loudiki, M. (2024). A Comprehensive Review of Microalgae and Cyanobacteria-Based Biostimulants for Agriculture Uses. Plants, 13(2), 159.

Chabili, A., Minaoui, F., Hakkoum, Z., Douma, M., Meddich, A., and Loudiki, M. (2024). A Comprehensive Review of Microalgae and Cyanobacteria-Based Biostimulants for Agriculture Uses. *Plants*, *13*(2), 159.

Chanda, M. J., Merghoub, N., and El Arroussi, H. (2019). Microalgae polysaccharides: the new sustainable bioactive products for the development of plant bio-stimulants?. *World Journal of Microbiology and Biotechnology*, *35*(11), 177.

Chaudhary, V., Prasanna, R., Nain, L., Dubey, S. C., Gupta, V., Singh, R., ... and Bhatnagar, A. K. (2012). Bioefficacy of novel cyanobacteria-amended formulations in suppressing damping off disease in tomato seedlings. *World Journal of Microbiology and Biotechnology*, *28*, 3301-3310.

Chekroun KB, Sánchez E, Baghour M (2014) The role of algae in bioremediation of organic pollutants. Int Res J Public Environ Health 1(2):19–32

Chiaiese, P., Corrado, G., Colla, G., Kyriacou, M. C., and Rouphael, Y. (2018). Renewable sources of plant biostimulation: microalgae as a sustainable means to improve crop performance. *Frontiers in plant science*, *9*, 430391.

Chuah, L. O., Effarizah, M. E., Goni, A. M., and Rusul, G. (2016). Antibiotic application and emergence of multiple antibiotic resistance (MAR) in global catfish aquaculture. Curr. Environ. Health Rep. 3 (2), 118–127.

Colla, G., Rouphael, Y., Canaguier, R., Svecova, E., and Cardarelli, M. (2014). Biostimulant action of a plant-derived protein hydrolysate produced through enzymatic hydrolysis. *Frontiers in plant science*, *5*, 110917.

Colla, G., Rouphael, Y., Lucini, L., Canaguier, R., Stefanoni, W., Fiorillo, A., et al. (2016). Protein hydrolysate-based biostimulants: origin, biological activity and application methods. *Acta Hortic.* 1148, 27–34. doi: 10.17660/ActaHortic.2016.1148.3

Colla, G., Svecova, E., Rouphael, Y., Cardarelli, M., Reynaud, H., Canaguier, R., et al. (2013). Effectiveness of a plant-derived protein hydrolysate to improve crop performances under different growing conditions. Acta Hortic. 1009, 175–179. doi: 10.17660/actahortic.2013.1009.21

Cordell, D., Rosemarin, A., Schröder, J. J., and Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, *84*(6), 747-758.

Costa, O. Y., Raaijmakers, J. M., and Kuramae, E. E. (2018). Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. *Frontiers in microbiology*, *9*, 337094.

Cressie, N. (2018). Mission CO2ntrol: A statistical scientist's role in remote sensing of atmospheric carbon dioxide. Journal of the American Statistical Association, 113(521), 152-168.

Crews, T. E., and Brookes, P. C. (2014). Changes in soil phosphorus forms through time in perennial versus annual agroecosystems. *Agriculture, Ecosystems and Environment*, *184*, 168-181.

Dantas, D. M. D. M., Oliveira, C. Y. B. D., Costa, R. M. P. B., Carneiro-da-Cunha, M. D. G., Gálvez, A. O., and Bezerra, R. D. S. (2019). Evaluation of antioxidant and antibacterial capacity of green microalgae Scenedesmus subspicatus. Food Sci. Technol. Int. 25 (4), 318–326.

de Morais, M.G., Costa, J.A.V., 2017a. Isolation and selection of microalgae from coal fired thermoelectric power plant for biofixation of carbon dioxide. Energy Convers. Manag. 48, 2169e2173. https://doi.org/10.1016/ j.enconman.2006.12.011.

de Morais, M.G., Costa, J.A.V., 2017b. Biofixation of carbon dioxide by Spirulina sp. and Scenedesmus obliquus cultivated in a three-stage serial tubular photo- bioreactor. J. Biotechnol. 129, 439e445. https://doi.org/10.1016/ j.jbiotec.2007.01.009.

Delattre, C., Pierre, G., Laroche, C., and Michaud, P. (2016). Production, extraction and characterization of microalgal and cyanobacterial exopolysaccharides. *Biotechnology advances*, *34*(7), 1159-1179.

Demirbas, A., and Demirbas, M. F. (2011). Importance of algae oil as a source of biodiesel. *Energy conversion and management*, *52*(1), 163-170.

Desbois, A. P., and Smith, V. J. (2010). Antibacterial free fatty acids: activities, mechanisms of action and biotechnological potential. Applied microbiology and biotechnology, 85, 1629-1642.

Doamekpor, L. K., Onwona-Agyeman, R., and Ameka, G. K. (2019). Bioenergy: Biodiesel from Freshwater Green *Microalgae* and a Cyanobacterium Occurring in Ghana. *West African Journal of Applied Ecology*, *27*(2), 51-60.

Dosnon-Olette R, Couderchet M, El Arfaoui A, Sayen S, Eullaffroy P (2010a) Influence of initial pesticide concentrations and plant population density on dimethomorph toxicity and removal by two duckweed species. Sci Total Environ 408:2254–2259

Dosnon-Olette R, Trotel-Aziz P, Couderchet M, Eullaffroy P (2010b) Fungicides and herbicide removal in Scenedesmus cell suspensions. Chemosphere 79(2):117–123.

Duff, D. A., Bruce, D. L., and Antia, N. J. (1966). The antibacterial activity of marine planktonic algae. *Canadian Journal of Microbiology*, *12*(5), 877-884.

Dussault, D., Vu, K. D., Vansach, T., Horgen, F. D., and Lacroix, M. (2016). Antimicrobial effects of marine algal extracts and cyanobacterial pure compounds against five foodborne pathogens. *Food chemistry, 199,* 114-118.

Dvir, I., Stark, A. H., Chayoth, R., Madar, Z., and Arad, S. M. (2009). Hypocholesterolemic effects of nutraceuticals produced from the red microalga Porphyridium sp in rats. *Nutrients*, *1*(2), 156-167.

El Arroussi, H., Benhima, R., Elbaouchi, A., Sijilmassi, B., El Mernissi, N., Aafsar, A., ... and Smouni, A. (2018). Dunaliella salina exopolysaccharides: a promising biostimulant for salt stress tolerance in tomato (Solanum lycopersicum). *Journal of Applied Phycology*, *30*, 2929-2941.

Elarroussia, H., Elmernissia, N., Benhimaa, R., El Kadmiria, I. M., Bendaou, N., Smouni, A., and Wahbya, I. (2016). Microalgae polysaccharides a promising plant growth biostimulant. *J. Algal Biomass Utln*, *7*(4), 55-63.

El-Baz, F. K., El-Senousy, W. M., El-Sayed, A. B., and Kamel, M. M. (2013). In vitro antiviral and antimicrobial activities of Spirulina platensis extract. *J. Appl. Pharm. Sci*, *3*(12), 52-56.

Eleiwa, N.Z.; Galal, A.A.A.; Abd El-Aziz, R.M. and Hussin, E.M. (2018). Antioxidant activity of *Spirulina platensis* alleviates doxorubicin induced oxidative stress and reprotoxicity in male rats. Orient. Pharm. Exp. Med., 18: 87- 95.

Eloka-Eboka, A. C., and Inambao, F. L. (2017). Effects of CO2 sequestration on lipid and biomass productivity in microalgal biomass production. Applied Energy, 195, 1100-1111.

El-Sheekh, M. M., Osman, M. E., Dyab, M. A., and Amer, M. S. (2006). Production and characterization of antimicrobial active substance from the cyanobacterium Nostoc muscorum. *Environmental toxicology and pharmacology*, *21*(1), 42-50.

Ertani, A., Sambo, P., Nicoletto, C., Santagata, S., Schiavon, M., and Nardi, S. (2015). The use of organic biostimulants in hot pepper plants to help low input sustainable agriculture. *Chemical and Biological Technologies in Agriculture*, *2*, 1-10.

Esquivel-Hernández, D. A., Ibarra-Garza, I. P., Rodriguez-Rodriguez, J., Cuéllar-Bermúdez, S. P., Rostro-Alanis, M. D. J., Alemán-Nava, G. S., ... and Parra-

Saldívar, R. (2017). Green extraction technologies for high-value metabolites from algae: a review. Biofuels, Bioprod Biorefin 11: 215–231.

Falaise, C., François, C., Travers, M. A., Morga, B., Haure, J., Tremblay, R., ... and Mouget, J. L. (2016). Antimicrobial compounds from eukaryotic microalgae against human pathogens and diseases in aquaculture. *Marine drugs*, *14*(9), 159.

Farid, R., Mutale-Joan, C., Redouane, B., Mernissi Najib, E. L., Abderahime, A., Laila, S., and Arroussi Hicham, E. L. (2019). Effect of microalgae polysaccharides on biochemical and metabolomics pathways related to plant defense in Solanum lycopersicum. *Applied biochemistry and biotechnology*, *188*, 225-240.

Feller, R., Matos, Â. P., Mazzutti, S., Moecke, E. H., Tres, M. V., Derner, R. B., ... and Junior, A. F. (2018). Polyunsaturated ω-3 and ω-6 fatty acids, total carotenoids and antioxidant activity of three marine microalgae extracts obtained by supercritical CO2 and subcritical n-butane. *The Journal of Supercritical Fluids*, *133*, 437-443.

Ferreira, A., Bastos, C. R., Marques-dos-Santos, C., Acién-Fernandez, F. G., and Gouveia, L. (2023). Algaeculture for agriculture: from past to future. *Frontiers in Agronomy*, *5*, 1064041.

Foo, S. C., Yusoff, F. M., Ismail, M., Basri, M., Yau, S. K., Khong, N. M., ... and Ebrahimi, M. (2017). Antioxidant capacities of fucoxanthin-producing algae as influenced by their carotenoid and phenolic contents. *Journal of biotechnology*, *241*, 175-183.

Galasso, C., Corinaldesi, C., and Sansone, C. (2017). Carotenoids from marine organisms: Biological functions and industrial applications. *Antioxidants*, *6*(4), 96.

Garcia-Gonzalez, J., and Sommerfeld, M. (2016). Biofertilizer and biostimulant properties of the microalga Acutodesmus dimorphus. *Journal of Applied Phycology*, *28*(2), 1051–1061.

Gattullo, C. E., Bährs, H., Steinberg, C. E., and Loffredo, E. (2012). Removal of bisphenol A by the freshwater green alga Monoraphidium braunii and the role of natural organic matter. *Science of the Total Environment*, *416*, 501-506.

Ge, S., Madill, M., and Champagne, P. (2018). Use of freshwater *macroalgae Spirogyra* sp. for the treatment of municipal wastewaters and biomass production for biofuel applications. *Biomass and bioenergy*, *111*, 213-223.

Geisler, G. (2003). Lea, PJ and Morot-Gaudry, J.-F.(eds) 2001: Plant Nitrogen.

Gershenzon, J., and Dudareva, N. (2007). The function of terpene natural products in the natural world. *Nature chemical biology, 3*(7), 408-414.

Ghumare, V. I. K. A. S., Rana, M. A. N. I. S. H. A., Gavkare, O. M. K. A. R., and Khachi, B. A. B. I. T. A. (2014). Bio-fertilizers-increasing soil fertility and crop productivity. Journal of Industrial Pollution Control, 30(2), 196-201.

Goiris, K., Muylaert, K., Fraeye, I., Foubert, I., De Brabanter, J., and De Cooman, L. (2012). Antioxidant potential of microalgae in relation to their phenolic and carotenoid content. *Journal of applied phycology*, *24*, 1477-1486.

Gonçalves, A. L. (2021). The use of microalgae and cyanobacteria in the improvement of agricultural practices: a review on their biofertilising, biostimulating and biopesticide roles. *Applied Sciences*, *11*(2), 871.

González, A., Castro, J., Vera, J., and Moenne, A. (2013). Seaweed oligosaccharides stimulate plant growth by enhancing carbon and nitrogen assimilation, basal metabolism, and cell division. *Journal of Plant Growth Regulation*, *32*, 443-448.

Górka, B., Korzeniowska, K., Lipok, J., and Wieczorek, P. P. (2018). The Biomass of algae and algal extracts in agricultural production. *Algae biomass: Characteristics and applications: Towards algae-based products*, 103-114.

Gouveia, L., and Gouveia, L. (2011). *Microalgae as a Feedstock for Biofuels* (pp. 1-69). Springer Berlin Heidelberg.

Guilherme, M. R., Aouada, F. A., Fajardo, A. R., Martins, A. F., Paulino, A. T., Davi, M. F., ... and Muniz, E. C. (2015). Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. *European Polymer Journal*, *72*, 365-385.

Gupta, V., Prasanna, R., Natarajan, C., Srivastava, A. K., and Sharma, J. (2010). Identification, characterization, and regulation of a novel antifungal chitosanase gene (cho) in Anabaena spp. *Applied and Environmental Microbiology*, *76*(9), 2769-2777.

Guzmán, S., Gato, A., Lamela, M., Freire-Garabal, M., and Calleja, J. M. (2003). Anti-inflammatory and immunomodulatory activities of polysaccharide from Chlorella stigmatophora and Phaeodactylum tricornutum. *Phytotherapy Research*, *17*(6), 665-670.

Hamed, S. M., El Shimi, H. I., van Dijk, J. R., Osman, A. I., Korany, S. M., and AbdElgawad, H. (2022a). A novel integrated system for heavy metals removal and biodiesel production via green microalgae: a techno-economic feasibility assessment. Journal of Environmental Chemical Engineering, 10(6), 108804.

Hamed, S. M., El-Gaml, N. M., and Eissa, S. T. (2022b). Integrated biofertilization using yeast with cyanobacteria on growth and productivity of wheat. Beni-Suef University Journal of Basic and Applied Sciences, 11(1), 112.

Hamed, S. M., Hassan, S. H., Selim, S., Wadaan, M. A., Mohany, M., Hozzein, W. N., and AbdElgawad, H. (2020). Differential responses of two cyanobacterial species to R-metalaxyl toxicity: Growth, photosynthesis and antioxidant analyses. Environmental pollution, 258, 113681.

Hamed, S. M., Kamal, M., and Messiha, N. A. (2023). Potential of algal-based products for the management of potato brown rot disease. Botanical Studies, 64(1), 29.

Hamed, S. M., Mohamed, M. Y. A., Alammari, B. S., and AbdElgawad, H. (2024). Insights into the growth and biochemical defense responses associated with fenitrothion toxicity and uptake by freshwater cyanobacteria. Chemosphere, 358, 141909.

Han, T., Zhao, Z., and Wang, Y. (2016). The effect of ryegrass and fertilizer on the petroleum contaminated soil remediation. *Feb Fresenius Environ Bull*, *25*(6), 2243-2250.

Han, X., Zeng, H., Bartocci, P., Fantozzi, F., and Yan, Y. (2018). Phytohormones and effects on growth and metabolites of microalgae: a review. *Fermentation*, *4*(2), 25.

Hangjun, Z., Xiaojun, J., Liping, L., and Wenfeng, W. (2015). Biodegradation of polychlorinated biphenyls (PCBs) by the novel identified cyanobacterium Anabaena PD-1. PLoS ONE 10 (7).

Hariz, H. B., and Takriff, M. S. (2017). Palm oil mill effluent treatment and CO 2 sequestration by using microalgae—sustainable strategies for environmental protection. Environmental Science and Pollution Research, 24, 20209-20240.

He, J., Wang, J., Deng, S., ZHAO, R., and ZHAO, L. (2017). Research progress on energy-efficiency analysis of carbon capture: theoretical model, evaluation tool and developing trend. Chem. Ind. Eng. Prog.(In Chinese).

Himani Priya, H. P., Radha Prasanna, R. P., Balasubramanian Ramakrishnan, B. R., Ngangom Bidyarani, N. B., Santosh Babu, S. B., Shobit Thapa, S. T., and Nirmal Renuka, N. R. (2015). Influence of cyanobacterial inoculation on the culturable microbiome and growth of rice.

Ho, S. H., Chen, Y. D., Chang, C. Y., Lai, Y. Y., Chen, C. Y., Kondo, A., ... and Chang, J. S. (2017). Feasibility of CO 2 mitigation and carbohydrate production by microalga Scenedesmus obliquus CNW-N used for bioethanol fermentation under outdoor conditions: effects of seasonal changes. Biotechnology for Biofuels, 10, 1-13.

Horváth, N., Katona, S., Berthold, D. E., Molnár, Z., Bálint, P., Ördög, V., ... and Laughinghouse IV, H. D. (2019). The reclassification of 37 strains from The Mosonmagyaróvár Algal Culture Collection, Hungary, which were previously identified as Anabaena (Cyanobacteria, Nostocaceae). South African journal of botany, 123, 333-340.

Ibrahim, W. M., Karam, M. A., El-Shahat, R. M., and Adway, A. A. (2014). Biodegradation and utilization of organophosphorus pesticide malathion by cyanobacteria. Biomed. Res. Int. 1-6, 392682.

Jiajun, H., Hongcheng, G., Yiyun, X., Min-tian, G., Shiping, Z., Tsang, Y. F., et al. (2019). Using a mixture of microalgae, biochar, and organic manure to increase the capacity of soil to act as carbon sink. J. Soils Sediments 19 (11), 3718–3727.

Kabra, A. N., Ji, M. K., Choi, J., Kim, J. R., Govindwar, S. P., & Jeon, B. H. (2014). Toxicity of atrazine and its bioaccumulation and biodegradation in a green microalga, Chlamydomonas mexicana. *Environmental Science and Pollution Research*, *21*, 12270-12278.

Kalyanasundaram, G. T., Ramasamy, A., Rakesh, S., and Subburamu, K. (2020). *Microalgae* and *cyanobacteria*: Role and applications in agriculture. Applied Algal Biotechnology; Nova Science Publishers: Hauppauge, NY, USA.

Kang, Y., Kim, M., Shim, C., Bae, S., and Jang, S. (2021). Potential of Algae–Bacteria Synergistic Effects on Vegetable Production. *Frontiers in Plant Science*, *12*(4), 1–13.

Kaushik, B. D. (2009). Developments in cyanobacterial biofertilizer. Algal Biology and Biotechnology. New Delhi: IK International Publishing House Pvt. Ltd, 97-108.

Khoddami, A., Wilkes, M. A., and Roberts, T. H. (2013). Techniques for analysis of plant phenolic compounds. *Molecules*, *18*(2), 2328-2375.

Kholssi, R., Marks, E. A. N., Miñón, J., Montero, O., Debdoubi, A., and Rad, C. (2019). Biofertilizing Effect of Chlorella sorokiniana Suspensions on Wheat Growth. *Journal of Plant Growth Regulation*, *38*(2), 644–649.

Kiki, C., Rashid, A., Wang, Y., Li, Y., Zeng, Q., Yu, C. P., et al. (2020). Dissipation of antibiotics by microalgae: Kinetics, identification of transformation products and pathways. J. Hazard. Mat. 387, 121985.

Kim, J. D. (2006). Screening of cyanobacteria (blue-green algae) from rice paddy soil for antifungal activity against plant pathogenic fungi. *Mycobiology*, *34*(3), 138-142.

Klinthong, W., Yang, Y. H., Huang, C. H., and Tan, C. S. (2015). A review: microalgae and their applications in CO2 capture and renewable energy. Aerosol and Air Quality Research, 15(2), 712-742.

Kobayashi, H., and Rittmann, B. E. (1982). Microbial removal of hazardous organic compounds. *Environmental Science and Technology*, *16*(3), 170A-183A.

Kobayashi, H., and Rittmann, B. E. (1982). Microbial removal of hazardous organic compounds. *Environmental Science and Technology*, *16*(3), 170A-183A.

Kratzer, R., and Murkovic, M. (2021). Food ingredients and nutraceuticals from microalgae: Main product classes and biotechnological production. *Foods*, *10*(7), 1626.

Kroumov, A. D., Módenes, A. N., Trigueros, D. E. G., Espinoza-Quiñones, F. R., Borba, C. E., Scheufele, F. B., and Hinterholz, C. L. (2016). A systems approach for CO2 fixation from flue gas by microalgae—Theory review. Process Biochemistry, 51(11), 1817-1832.

Kubota, T., Iwai, T., Sakai, K., Gonoi, T., and Kobayashi, J. I. (2014). Amphidinins C–F, Amphidinolide Q Analogues from Marine Dinoflagellate Amphidinium sp. *Organic letters*, *16*(21), 5624-5627.

Kulasooriya, S. A., and Magana-Arachchi, D. N. (2016). Nitrogen fixing cyanobacteria: their diversity, ecology and utilisation with special reference to rice cultivation.

Kumar K, Verma PK (2013) Plant pathogen interactions: crop improvement under adverse conditions. In: Tuteja N, Gill SS (eds) Plant acclimation to environmental stress. Springer, New York, pp 433–459

Kumar, D., Kastanek, P., and Adhikary, S. P. (2018). Exopolysaccharides from cyanobacteria and microalgae and their commercial application. Curr. Sci. 115 (2), 234–241.

Kumar, J., Ramlal, A., Mallick, D., and Mishra, V. (2021). An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants*, *10*(6), 1185.

Kumar, M., Karthikeyan, N., and Prasanna, R. (2016). Priming of plant defense and plant growth in disease-challenged crops using microbial consortia. Microbial-mediated Induced Systemic Resistance in Plants, 39-56.

Kumar, M., Prasanna, R., Bidyarani, N., Babu, S., Mishra, B. K., Kumar, A., ... and Saxena, A. K. (2013). Evaluating the plant growth promoting ability of thermotolerant bacteria and cyanobacteria and their interactions with seed spice crops. *Scientia Horticulturae*, *164*, 94-101.

Kushwaha, O. S., Uthayakumar, H., and Kumaresan, K. (2021). Modeling of carbon dioxide fixation rate by micro algae using hybrid Artificial Intelligence and Fuzzy Logic methods and optimization by Genetic Algorithm

La Bella, E., Baglieri, A., Fragalà, F., and Puglisi, I. (2022). Multipurpose agricultural reuse of microalgae biomasses employed for the treatment of urban wastewater. Agronomy, 12(2), 234.

Lam, M. K., and Lee, K. T. (2012). Microalgae biofuels: a critical review of issues, problems and the way forward. *Biotechnology advances*, *30*(3), 673-690.

Lau, N. S., Matsui, M., and Abdullah, A. A. A. (2015). Cyanobacteria: photoautotrophic microbial factories for the sustainable synthesis of industrial products. BioMed research international, 2015.

Lawton, R. J., De Nys, R., and Paul, N. A. (2013). Selecting reliable and robust freshwater *macroalgae* for biomass applications. *PloS one*, *8*(5), e64168.

Leong, Y. K., and Chang, J. S. (2020). Bioremediation of heavy metals using microalgae: Recent advances and mechanisms. Bioresour. Technol. 303, 122886.

Lijian, L., Liang, W., Qin, X., Siyu, X., Wenting, L., Sen, L., et al. (2020). Use of microalgae based technology for the removal of antibiotics from wastewater: A review. Chemosphere 238, 124680.

Lu, Y., and Xu, J. (2015). Phytohormones in microalgae: a new opportunity for microalgal biotechnology?. *Trends in plant science*, *20*(5), 273-282.

Mager, D. M., and Thomas, A. D. (2011). Extracellular polysaccharides from cyanobacterial soil crusts: A review of their role in dryland soil processes. J. Arid. Environ. 75 (2), 91–97.

Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., and Tribedi, P. (2017). Biofertilizers: a potential approach for sustainable agriculture development. Environmental Science and Pollution Research, 24, 3315-3335

Mandal, S., and Mallick, N. (2014). *Microalgae*: The tiny microbes with a big impact. In *Bioenergy Research: Advances and Applications* (pp. 171-184). Elsevier.

Marangoni, A., Foschi, C., Micucci, M., Nahui Palomino, R. A., Gallina Toschi, T., Vitali, B., ... and Budriesi, R. (2017). In vitro activity of Spirulina platensis water extract against different Candida species isolated from vulvo-vaginal candidiasis cases. *PLoS One*, *12*(11), e0188567.

Marks, E. A., Montero, O., and Rad, C. (2019). The biostimulating effects of viable microalgal cells applied to a calcareous soil: Increases in bacterial biomass, phosphorus scavenging, and precipitation of carbonates. Sci. Total Environ. 692, 784–790.

Marrez, D. A., and Sultan, Y. Y. (2016). Antifungal activity of the cyanobacterium Microcystis aeruginosa against mycotoxigenic fungi. *Journal of Applied Pharmaceutical Science*, *6*(11), 191-198.

Maschek, J. A., and Baker, B. J. (2008). The chemistry of algal secondary metabolism. In *Algal chemical ecology* (pp. 1-24). Berlin, Heidelberg: Springer Berlin Heidelberg.

Megharaj, M., Kantachote, D., Singleton, I., and Naidu, R. (2000). Effects of long-term contamination of DDT on soil microflora with special reference to soil algae and algal transformation of DDT. *Environmental Pollution*, *109*(1), 35-42.

Mehta, S., and Nautiyal, C. S. (2001). An efficient method for qualitative screening of phosphate-solubilizing bacteria. *Current microbiology*, *43*, 51-56.

Mfarrej, M. F. B., and Rara, F. M. (2019). Competitive, sustainable natural pesticides. Acta Ecol. Sin. 39 (2), 145–1.

Michalak, I., Chojnacka, K., and Saeid, A. (2017). Plant growth biostimulants, dietary feed supplements and cosmetics formulated with supercritical CO2 algal extracts. *Molecules*, *22*(1), 66.

Mishra, A. K., Tiwari, D. N., and Rai, A. N. (Eds.). (2018). *Cyanobacteria: from basic science to applications*. Academic Press.

Miškovičová, V., and Masojídek, J. (2023). Transdisciplinary collaboration in architecture: Integrating microalgae biotechnologies for human and non-human perspectives. *Architecture Papers of the Faculty of Architecture and Design STU*, *28*(2), 10-20.

Mohapatra, S., and Kirpalani, D. M. (2021). Microalgae and cyanobacteria for agrochemical degradation: towards sustainable agriculture. In Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment (pp. 639-655). Springer, Singapore.

Mona, S., Kumar, V., Deepak, B., and Kaushik, A. (2020). Cyanobacteria: the eco-friendly tool for the treatment of industrial wastewaters. *Bioremediation of Industrial Waste for Environmental Safety: Volume II: Biological Agents and Methods for Industrial Waste Management*, 389-413.

Moore, R. E., Corbett, T. H., Patterson, G. M., and Valeriote, F. A. (1996). The search for new antitumor drugs from blue-green algae. *Current Pharmaceutical Design*, *2*(3), 317-330.

Nagarajan, M., Maruthanayagam, V., and Sundararaman, M. (2013). SAR analysis and bioactive potentials of freshwater and terrestrial cyanobacterial compounds: a review. *Journal of applied toxicology*, *33*(5), 313-349.

Nannipieri, P., Giagnoni, L., Landi, L., and Renella, G. (2011). Phosphorus in action. *Soil Biol*, *26*, 215-243.

National Oceanic and Atmospheric Administration. (2020). Trends in atmospheric carbon dioxide. In: Earth System Research Laboratory

Oksana, S., Marian, B., Mahendra, R., and Bo, S. H. (2012). Plant phenolic compounds for food, pharmaceutical and cosmetics production. *Journal of Medicinal Plants Research*, *6*(13), 2526-2539.

Olaizola, M. (2003). Commercial development of *microalgal* biotechnology: from the test tube to the marketplace. *Biomolecular engineering*, *20*(4-6), 459-466.

Ördög, V., Stirk, W. A., Van Staden, J., Novák, O., and Strnad, M. (2004). Endogenous cytokinins in three genera of microalgae from the Chlorophyta 1. *Journal of Phycology*, *40*(1), 88-95.

Ortiz-Moreno, M. L., Sandoval-Parra, K. X., and Solarte- Murillo, L. V. (2019). Chlorella, a potential biofertilizer? *Orinoquia*, *23*(2), 71–78.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... and van Ypserle, J. P. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). Ipcc.

Pan, S., Jeevanandam, J., and Danquah, M. K. (2019). Benefits of algal extracts in sustainable agriculture. *Grand Challenges in Algae Biotechnology*, 501-534.

Pattanaik, B., and Lindberg, P. (2015). Terpenoids and their biosynthesis in cyanobacteria. *Life*, *5*(1), 269-293.

Pavela *et a*l.,2016; Pattanaik *et al*.,2015; Gershenzon and Dudareva, 2007

Pavela, R., and Benelli, G. (2016). Essential oils as ecofriendly biopesticides? Challenges and constraints. *Trends in plant science*, *21*(12), 1000-1007.

Pawar, S. T., and Puranik, P. R. (2008). Screening of terrestrial and freshwater halotolerant cyanobacteria for antifungal activities. *World Journal of Microbiology and Biotechnology*, *24*, 1019-1025.

Pan, S., Jeevanandam, J., and Danquah, M. K. (2019). Benefits of algal extracts in sustainable agriculture. *Grand Challenges in Algae Biotechnology*, 501-534.

Perera, I., Subashchandrabose, S. R., Venkateswarlu, K., Naidu, R., and Megharaj, M. (2018). Consortia of cyanobacteria/microalgae and bacteria in desert soils: an underexplored microbiota. *Applied microbiology and biotechnology*, *102*, 7351-7363.

Pinto, E., Sigaud-Kutner, T. C. S., Leitão, M. A. S., Okamoto, O. K., Morse, D., and Colepicolo, P. (2003). Heavy metal-induced oxidative stress in algae. Journal of Phycology, 39(6), 1008-1018.

Pinzón, A. Y., González-Delgadob, Á. D., and Kafarova, V. (2014). Optimization of microalgae composition for development of a topology of biorefinery based on profitability analysis. *CHEMICAL ENGINEERING*, *37*.

Pires, J. C. M., Gonçalves, A. L., Martins, F. G., Alvim-Ferraz, M. C. M., and Simões, M. (2014). Effect of light supply on CO 2 capture from atmosphere by Chlorella vulgaris and Pseudokirchneriella subcapitata. Mitigation and adaptation strategies for global change, 19, 1109-1117.

Pradhan, J., Das, S., and Das, B. K. (2014). Antibacterial activity of freshwater microalgae: A review. *African Journal of Pharmacy and Pharmacology*, *8*(32), 809-818.

Prasanna, R., Adak, A., Verma, S., Bidyarani, N., Babu, S., Pal, M., ... and Nain, L. (2015). Cyanobacterial inoculation in rice grown under flooded and SRI modes of cultivation elicits differential effects on plant growth and nutrient dynamics. Ecological engineering, 84, 532-541.

Prasanna, R., Chaudhary, V., Gupta, V., Babu, S., Kumar, A., Singh, R., ... and Nain, L. (2013). Cyanobacteria mediated plant growth promotion and bioprotection against Fusarium wilt in tomato. *European Journal of Plant Pathology*, *136*, 337-353.

Prasanna, R., Nain, L., Tripathi, R., Gupta, V., Chaudhary, V., Middha, S., ... and Kaushik, B. D. (2008). Evaluation of fungicidal activity of extracellular filtrates of cyanobacteria–possible role of hydrolytic enzymes. *Journal of basic microbiology*, *48*(3), 186-194.

Pratt, R., Daniels, T. C., Eiler, J. J., Gunnison, J. B., Kumler, W. D., Oneto, J. F., ... and Strain, H. H. (1944). Chlorellin, an antibacterial substance from Chlorella. *Science*, *99*(2574), 351-352.

Priatni, S., Ratnaningrum, D., Warya, S., and Audina, E. (2018). Phycobiliproteins production and heavy metals reduction ability of Porphyridium sp. IOP Conf. Ser. Earth Environ. Sci. 160, 012006.

Puglisi, I., Barone, V., Sidella, S., Coppa, M., Broccanello, C., Gennari, M., and Baglieri, A. (2018). Biostimulant activity of humic-like substances from agro-industrial waste on *Chlorella vulgaris* and *Scenedesmus quadricauda*. *European journal of phycology*, *53*(3), 433-442.

Qaswar, M., Chai, R., Ahmed, W., Jing, H., Han, T., Liu, K., ... and Zhang, H. (2020). Partial substitution of chemical fertilizers with organic amendments increased rice yield by changing phosphorus fractions and improving phosphatase activities in fluvo-aquic soil. *Journal of soils and sediments*, *20*, 1285-1296.

Rai, A. K. (2019). Agricultural nitrogen management for sustainable development and global food security. J. Sci. Res, 63, 79-87.

Rai, A. N., Singh, A. K., and Syiem, M. B. (2019). Plant growth-promoting abilities in cyanobacteria. In *Cyanobacteria* (pp. 459-476). Academic Press.

Raja, N. (2013). Biopesticides and biofertilizers: ecofriendly sources for sustainable agriculture. J Biofertil Biopestici, 4(1), 1-2.

Rajesh, K., Rohit, M. V., and Mohan, S. V. (2017). Microalgae-based carotenoids production. In *Algal green chemistry* (pp. 139-147). Elsevier.

Ramakrishnan, B., Maddela, N. R., Venkateswarlu, K., and Megharaj, M. (2023). Potential of microalgae and cyanobacteria to improve soil health and agricultural productivity: a critical view. Environmental Science: Advances, 2(4), 586-611.

Ramos, V. M., Castelo-Branco, R., Leao, P. N., Martins, J., Carvalhal-Gomes, S., Sobrinho da Silva, F., ... and Vasconcelos, V. M. (2017). Cyanobacterial diversity in microbial mats from the hypersaline lagoon system of Araruama, Brazil: An in-depth polyphasic study. *Frontiers in Microbiology*, *8*, 1233.

Rana, A., Joshi, M., Prasanna, R., Shivay, Y. S., and Nain, L. (2012). Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. European Journal of Soil Biology, 50, 118-126.

Rana, K. L., Kour, D., Sheikh, I., Yadav, N., Yadav, A. N., Kumar, V., ... and Saxena, A. K. (2019). Biodiversity of endophytic fungi from diverse niches and their biotechnological applications. Advances in endophytic fungal research: present status and future challenges, 105-144.

Ranglová, K., Lakatos, G. E., Manoel, J. A. C., Grivalský, T., Estrella, F. S., Fernández, F. G. A., ... and Masojídek, J. (2021). Growth, biostimulant and biopesticide activity of the MACC-1 Chlorella strain cultivated outdoors in inorganic medium and wastewater. *Algal research*, *53*, 102136.

Raposo, M. F. D. J., Morais, A. M. M. B. D., and Morais, R. M. S. C. D. (2015). Carotenoids from marine microalgae: A valuable natural source for the prevention of chronic diseases. *Marine drugs*, *13*(8), 5128-5155.

Ray, K., Mukherjee, C., and Ghosh, A. N. (2013). A way to curb phosphorus toxicity in the environment: use of polyphosphate reservoir of cyanobacteria and microalga as a safe alternative phosphorus biofertilizer for Indian agriculture.

Raymaekers K, Ponet L, Holtappels D, Berckmans B, Cammue BPA (2020) Screening for novel biocontrol agents applicable in plant disease management – a review. Biol Control 144:104240

Razzak, S. A., Hossain, M. M., Lucky, R. A., Bassi, A. S., and De Lasa, H. (2013). Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—a review. Renewable and sustainable energy reviews, 27, 622-653.

Rechter, S., König, T., Auerochs, S., Thulke, S., Walter, H., Dörnenburg, H., ... and Marschall, M. (2006). Antiviral activity of Arthrospira-derived spirulan-like substances. *Antiviral research*, *72*(3), 197-206.

Renuka, N., Guldhe, A., Prasanna, R., Singh, P., and Bux, F. (2018). Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. *Biotechnology advances*, *36*(4), 1255-1273.

Richmond, A. (Ed.). (2004). *Handbook of microalgal culture: biotechnology and applied phycology* (Vol. 577). Oxford: Blackwell science.

Righini, H., Francioso, O., Martel Quintana, A., and Roberti, R. (2022). Cyanobacteria: a natural source for controlling agricultural plant diseases caused by fungi and oomycetes and improving plant growth. *Horticulturae*, *8*(1), 58.

Righini, H., Francioso, O., Di Foggia, M., Quintana, A. M., and Roberti, R. (2020). Preliminary Study on the Activity of Phycobiliproteins against Botrytis cinerea. *Marine drugs*, *18*(12), 600.

Rodriguez-Garcia, A., Hosseini, S., Martinez-Chapa, S. O., and Cordell, G. A. (2017). Multi-target activities of selected alkaloids and terpenoids. *Mini-Reviews in Organic Chemistry*, *14*(4), 272-279.

Rojas, V., Rivas, L., Cárdenas, C., and Guzmán, F. (2020). Cyanobacteria and eukaryotic microalgae as emerging sources of antibacterial peptides. *Molecules*, *25*(24), 5804.

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

Ruangsomboon, S., Prachom, N., and Sornchai, P. (2017). Enhanced growth and hydrocarbon production of Botryococcus braunii KMITL 2 by optimum carbon dioxide concentration and concentration-dependent effects on its biochemical composition and biodiesel properties. Bioresource technology, 244, 1358-1366.

Sahin, D., Taskan, E., and Taskan, B. (2018). Biodegradation of agrochemical pollutants by microalgae. In Handbook of Algal Technologies (pp. 305-337). Springer, Singapore.

Saiz, E., Sgouridis, F., Drijfhout, F. P., and Ullah, S. (2019). Biological nitrogen fixation in peatlands: comparison between acetylene reduction assay and 15N2 assimilation methods. Soil Biology and Biochemistry, 131, 157-165

Sakamoto, Y., Mori, K., Matsuo, Y., Mukojima, N., Watanabe, W., Sobaru, N., ... and Chaya, M. (2017). Breeding of a new potato variety 'Nagasaki Kogane'with high eating quality, high carotenoid content, and resistance to diseases and pests. *Breeding science*, *67*(3), 320-326.

Sandhya, S. V., and Vijayan, K. K. (2019). Symbiotic association among marine microalgae and bacterial flora: A study with special reference to commercially important isochrysis galbana culture. J. Appl. Phycol. 31 (4), 2259–2266.

Santoyo, S., Rodríguez-Meizoso, I., Cifuentes, A., Jaime, L., Reina, G. G. B., Señorans, F. J., and Ibáñez, E. (2009). Green processes based on the extraction with pressurized fluids to obtain potent antimicrobials from Haematococcus pluvialis microalgae. *LWT-Food Science and Technology*, *42*(7), 1213-1218.

Sarma, M. K., Kaushik, S., and Goswami, P. (2016). Cyanobacteria: A metabolic power house for harvesting solar energy to produce bio-electricity and biofuels. Biomass and Bioenergy, 90, 187-201.

Sarwer, A., Hamed, S. M., Osman, A. I., Jamil, F., Al-Muhtaseb, A. A. H., Alhajeri, N. S., & Rooney, D. W. (2022). Algal biomass valorization for biofuel production and carbon sequestration: a review. Environmental Chemistry Letters, 20(5), 2797-2851.

Sathasivam, R., Radhakrishnan, R., Hashem, A., Elsayed, F., and Allah, E. F. (2019). Review micro- algae metabolites: A rich source for food and medicine. *Saudi Journal of Biological Sciences, 26*, 709–722.

Schenk, P. M., Thomas-Hall, S. R., Stephens, E., Marx, U. C., Mussgnug, J. H., Posten, C., ... and Hankamer, B. (2008). Second generation biofuels: high-efficiency microalgae for biodiesel production. *Bioenergy research*, *1*, 20-43.

Senhorinho, G. N., Ross, G. M., and Scott, J. A. (2015). Cyanobacteria and eukaryotic microalgae as potential sources of antibiotics. *Phycologia*, *54*(3), 271-282.

Shah, S. A. A., Akhter, N., Auckloo, B. N., Khan, I., Lu, Y., Wang, K., ... and Guo, Y. W. (2017). Structural diversity, biological properties and applications of natural products from cyanobacteria. A review. *Marine Drugs*, *15*(11), 354.

Shan, C., Jiayuan, L., Wenbo, F., Mingzhe, Y., Zhang, W., Houtao, X., et al. (2020). Biochemical responses of the freshwater microalga Dictyosphaerium sp. upon exposure to three sulfonamides. J. Environ. Sci. 97, 141–148.

Shannon, E., and Abu-Ghannam, N. (2016). Antibacterial derivatives of marine algae: An overview of pharmacological mechanisms and applications. *Marine drugs*, *14*(4), 81.

Shen, C., Shen, J., Zhu, Y., and Wang, J. (2022). Microalgae-based bioremediation of agrochemicals: mechanisms and applications. Environmental Technology and Innovation, 25, 102176.

Shen, Q. H., Jiang, J. W., Chen, L. P., Cheng, L. H., Xu, X. H., and Chen, H. L. (2015). Effect of carbon source on biomass growth and nutrients removal of Scenedesmus obliquus for wastewater advanced treatment and lipid production. Bioresource Technology, 190, 257-263.

Sherpa, R. T., Reese, C. J., and Aliabadi, H. M. (2015). Application of iChip to grow “uncultivable” microorganisms and its impact on antibiotic discovery. J. Pharm. Pharm. Sci. 18 (3), 303–315.

Shishido, T. K., Humisto, A., Jokela, J., Liu, L., Wahlsten, M., Tamrakar, A., ... and Sivonen, K. (2015). Antifungal compounds from cyanobacteria. *Marine drugs*, *13*(4), 2124-2140.

Singh, B., Guldhe, A., Rawat, I., and Bux, F. (2014). Towards a sustainable approach for development of biodiesel from plant and microalgae. Renewable and sustainable Energy reviews, 29, 216-245.

Singh, H. M., Kothari, R., Gupta, R., and Tyagi, V. V. (2019). Bio-fixation of flue gas from thermal power plants with algal biomass: Overview and research perspectives. Journal of environmental management, 245, 519-539.

Singh, J. S., Kumar, A., Rai, A. N., and Singh, D. P. (2016). Cyanobacteria: a precious bio-resource in agriculture, ecosystem, and environmental sustainability. Frontiers in microbiology, 7, 186282.

Singh, J. S., Kumar, A., Rai, A. N., and Singh, D. P. (2016). Cyanobacteria: A Precious Bio-resource in Agriculture, Ecosystem, and Environmental Sustainability. Frontiers in microbiology, 7, 529.

Singh, R., Parihar, P., Singh, M., Bajguz, A., Kumar, J., Singh, S., ... and Prasad, S. M. (2017). Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture and medicine: current status and future prospects. *Frontiers in microbiology*, *8*, 212348.

Singh, R. K., Tiwari, S. P., Rai, A. K., and Mohapatra, T. M. (2011). Cyanobacteria: an emerging source for drug discovery. *The Journal of antibiotics*, *64*(6), 401-412.

Singh, S. K., Rahman, A., Dixit, K., Nath, A., and Sundaram, S. (2016). Evaluation of promising algal strains for sustainable exploitation coupled with CO2 fixation. Environmental technology, 37(5), 613-622.

Song, X., Bo, Y., Feng, Y., Tan, Y., Zhou, C., Yan, X., ... and Cheng, P. (2022). Potential applications for multifunctional microalgae in soil improvement. *Frontiers in Environmental Science*, *10*, 1035332.

Spolaore, P., Joannis-Cassan, C., Duran, E., and Isambert, A. (2006). Commercial applications of microalgae. *Journal of bioscience and bioengineering*, *101*(2), 87-96.

Stancheva, R., Sheath, R. G., Read, B. A., McArthur, K. D., Schroepfer, C., Kociolek, J. P., and Fetscher, A. E. (2013). Nitrogen-fixing cyanobacteria (free-living and diatom endosymbionts): their use in southern California stream bioassessment. Hydrobiologia, 720, 111-127.

Stavi, I., and Lal, R. (2015). Achieving zero net land degradation: Challenges and opportunities. J. Arid. Environ. 112, 44–51. 51.

SundarRajan, P., Gopinath, K. P., Greetham, D., and Antonysamy, A. J. (2019). A review on cleaner production of biofuel feedstock from integrated CO2 sequestration and wastewater treatment system. Journal of cleaner production, 210, 445-458.

Swain, S. S., Paidesetty, S. K., and Padhy, R. N. (2017). Antibacterial, antifungal and antimycobacterial compounds from cyanobacteria. *Biomedicine and Pharmacotherapy*, *90*, 760-776.

Tak, H. I., Ahmad, F., Babalola, O. O., and Inam, A. (2012). Growth, photosynthesis and yield of chickpea as influenced by urban wastewater and different levels of phosphorus. *International Journal of Plant Research*, *2*(2), 6-13.

Thoré, E. S., Muylaert, K., Bertram, M. G., and Brodin, T. (2023). Microalgae. *Current Biology*, *33*(3), R91-R95.

Tian, J., Ge, F., Zhang, D., Deng, S., and Liu, X. (2021). Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical P cycle. *Biology*, *10*(2), 158.

Tibbetts, S. M., Milley, J. E., and Lall, S. P. (2015). Chemical composition and nutritional properties of freshwater and marine microalgal biomass cultured in photobioreactors. *Journal of Applied Phycology*, *27*, 1109-1119.

Tiwari, A. and Sharma, A. (2013). Antifungal activity of *Anabaena variabilis* against plant pathogens. Int. J. Pharma Bio Sci., 4(2): 1030-1036.

Tiwari, B., Singh, S., Chakraborty, S., Verma, E., and Mishra, A. K. (2017). Sequential role of biosorption and biodegradation in rapid removal degradation and utilization of methyl parathion as a phosphate source by a new cyanobacterial isolate Scytonema sp. BHUS-5. Int. J. Phytoremediation 19 (10).

Tomaselli, L. (2004). The microalgal cell. *Handbook of microalgal culture: biotechnology and applied phycology, 1, 3-19.*

Toribio, A. J., Suárez-Estrella, F., Jurado, M. M., López, M. J., López-González, J. A., and Moreno, J. (2020). Prospection of cyanobacteria producing bioactive substances and their application as potential phytostimulating agents. *Biotechnology Reports*, *26*, e00449.

Touliabah, H. E., El-Sheekh, M. M., Ismail, M. M., and El-Kassas, H. (2022). A Review of Microalgae- and Cyanobacteria-Based Biodegradation of Organic Pollutants. *Molecules (Basel, Switzerland)*, *27*(3), 1141.

Upadhyay, A. K., Mandotra, S. K., Kumar, N., Singh, N. K., Singh, L., and Rai, U. N. (2016). Augmentation of arsenic enhances lipid yield and defense responses in alga Nannochloropsis sp. Bioresour. Technol. 221, 430–437.

Usman, A., Khalid, S., Usman, A., Hussain, Z., and Wang, Y. (2017). Algal polysaccharides, novel application, and outlook. In *Algae based polymers, blends, and composites* (pp. 115-153). Elsevier.

Vera, J., Castro, J., Gonzalez, A., and Moenne, A. (2011). Seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. *Marine drugs*, *9*(12), 2514-2525.

Wang, Z., Wen, X., Xu, Y., Ding, Y., Geng, Y., and Li, Y. (2018). Maximizing CO2 biofixation and lipid productivity of oleaginous microalga Graesiella sp. WBG1 via CO2-regulated pH in indoor and outdoor open reactors. Science of the total environment, 619, 827-833.

ER, W. C. (2019). WMO greenhouse gas bulletin.

Wei, G., Jia, Q., Chen, X., Köllner, T. G., Bhattacharya, D., Wong, G. K. S., ... and Chen, F. (2019). Terpene biosynthesis in red algae is catalyzed by microbial type but not typical plant terpene synthases. *Plant physiology*, *179*(2), 382-390.

Weisenburger D. D. (1993). Human health effects of agrichemical use. Human pathology, 24(6), 571–576.

WMO (World Meteorological Organization), 2019. World Meteorological Organi- zation Greenhouse Gas Bullutin (GHG Bulletin)- No. 15: the State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018.

WMO Greenhouse Gas Bulletin. (2012). The state of greenhouse gases in the atmosphere based on global observations through 2011

Xiaoyu, W., Meiyin, W., Lei, Z., Yongdong, D., Yang, H., Chenda, Y., et al. (2022). ALA_PDT promotes ferroptosis-like death of Mycobacterium abscessus and antibiotic sterilization via oxidative stress. Antioxidants 11 (3), 546.

Xie, E., Li, F., Wang, C., Shi, W., Huang, C., Fa, K., ... and Zhang, D. (2020). Roles of sulfur compounds in growth and alkaline phosphatase activities of Microcystis aeruginosa under phosphorus deficiency stress. *Environmental Science and Pollution Research*, *27*, 21533-21541.

Xie, E., Su, Y., Deng, S., Kontopyrgou, M., and Zhang, D. (2021). Significant influence of phosphorus resources on the growth and alkaline phosphatase activities of Microcystis aeruginosa. *Environmental pollution*, *268*, 115807.

Yadav, G., and Sen, R. (2017). Microalgal green refinery concept for biosequestration of carbon-dioxide vis-à-vis wastewater remediation and bioenergy production: Recent technological advances in climate research. Journal of CO2 Utilization, 17, 188-206.

Yadav, G., Karemore, A., Dash, S. K., and Sen, R. (2015). Performance evaluation of a green process for microalgal CO2 sequestration in closed photobioreactor using flue gas generated in-situ. Bioresource Technology, 191, 399-406.

Yadav, P., Singh, R. P., Patel, A. K., Pandey, K. D., and Gupta, R. K. (2022). Cyanobacteria as a Biocontrol Agent. In *Microbial Biocontrol: Food Security and Post Harvest Management: Volume 2* (pp. 167-185). Cham: Springer International Publishing.

Rath, B. (2012). Microalgal bioremediation: current practices and perspectives. *Journal of Biochemical Technology*, *3*(3), 299-304.

Sethunathan, N., Megharaj, M., Chen, Z. L., Williams, B. D., Lewis, G., and Naidu, R. (2004). Algal degradation of a known endocrine disrupting insecticide, α-endosulfan, and its metabolite, endosulfan sulfate, in liquid medium and soil. *Journal of agricultural and food chemistry*, *52*(10), 3030-3035.

Singh, D. V., Ali, R., Anita, Kulsum, M., and Bhat, R. A. (2020). Ecofriendly approaches for remediation of pesticides in contaminated environs. Bioremediation and Biotechnology, Vol 3: Persistent and Recalcitrant Toxic Substances, 173-194.

Volk, R. B., and Furkert, F. H. (2006). Antialgal, antibacterial and antifungal activity of two metabolites produced and excreted by cyanobacteria during growth. *Microbiological Research*, *161*(2), 180-186.

Weiner, J. A., DeLorenzo, M. E., and Fulton, M. H. (2004). Relationship between uptake capacity and differential toxicity of the herbicide atrazine in selected microalgal species. *Aquatic Toxicology, 68*(2), 121-128.

Yandigeri, M. S., Yadav, A. K., Srinivasan, R., Kashyap, S., and Pabbi, S. (2011). Studies on mineral phosphate solubilization by *cyanobacteria Westiellopsis* and *Anabaena*. *Microbiology*, *80*, 558-565.

Yoder, N., and Davis, J. G. (2020). Organic fertilizer comparison on growth and nutrient content of three kale cultivars. HortTechnology 30 (2), 176–184.

Zhou, W., Wang, J., Chen, P., Ji, C., Kang, Q., Lu, B., ... and Ruan, R. (2017). Bio-mitigation of carbon dioxide using microalgal systems: Advances and perspectives. Renewable and Sustainable Energy Reviews, 76, 1163-1175.