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The Potential Use of Cyanobacteria and Algae in the Biological Control of Plant Diseases

الاستخدام المحتمل للسيانوبكتريا والطحالب في المكافحة البيولوجية لأمراض النبات

A Graduation Research Project Submitted to the Department Biology in Partial Fulfilment 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 a bachelor's degree in biology

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بسم الله الرحمن الرحيم

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All praise is due to Allah, whose blessings complete all good deeds and whose grace makes matters easy. We thank Him for granting us knowledge, perseverance, and success to accomplish this undergraduate research work.

To our beloved homeland, which has generously provided us with knowledge and opportunities, we extend our deepest gratitude and pledge to honour its trust through our efforts.

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May Allah accept this effort and grant us all success in our future endeavours.

All praise is due to Allah, Lord of all worlds.

Abstract:

The increasing demand for safe food necessitates effective strategies to protect plants from diseases and pests, as traditional methods often fail to ensure both efficacy and safety. Thus, the use of bioproducts for pest control is seen as reasonable solution being environmentally friendly and less hazardous for human health. Among them, macroalgae (seaweeds), microalgae and cyanobacteria (blue-green algae) gain interest every year in the scientific community. In agriculture, seaweeds are used in the production of plant bioactive compounds to control some plant pathogenic fungi and bacteria while microalgae remain unexploited. Microalgae, cyanobacteria and seaweeds are widely described as renewable sources of biologically active compounds, such as polyunsaturated fatty acids (PUFAs), carotenoids, phycobiliproteins, sterols, vitamins and polysaccharides, which attract considerable interest in both scientific and agricultural communities. They affect agricultural crops for enhancement of plant growth, seedling growth and for biocontrol of bacterial, fungal, nematode diseases and insect invasions. They can also increase resistance properties of plant against various pests and diseases. The present review highlights the potential use of algae and cyanobacteria in agronomy, with a specific focus on their biological activities and their possible application in modern agricultural technology as a potentially sustainable alternative for enhanced crop performance, and resilience to plant diseases.

الخلاصة

إن الطلب المتزايد على الغذاء الآمن يستلزم استراتيجيات فعّالة لحماية النباتات من الأمراض والآفات، حيث تفشل الطرق التقليدية غالبًا في ضمان الفعالية والسلامة. وبالتالي، يُنظر إلى استخدام المنتجات الحيوية لمكافحة الآفات على أنه حل معقول صديق للبيئة وأقل ضررًا على صحة الإنسان. ومن بينها، تكتسب الطحالب الكبيرة (الأعشاب البحرية) والطحالب الدقيقة و السيانوبكتريا (الطحالب الخضراء المزرقة) اهتمامًا كل عام في المجتمع العلمي.

في الزراعة، تُستخدم الأعشاب البحرية في إنتاج المركبات الحيوية النشطة للنباتات للسيطرة على بعض الفطريات والبكتيريا المسببة للأمراض النباتية بينما تظل الطحالب الدقيقة غير مستغلة. توصف الطحالب الدقيقة والسيانوبكتريا والأعشاب البحرية على نطاق واسع بأنها مصادر متجددة للمركبات الحيوية النشطة، مثل الأحماض الدهنية المتعددة غير المشبعة (PUFAs)، والكاروتينات، والبروتينات النباتية، والستيرولات، والفيتامينات، والسكريات المتعددة، والتي تجذب اهتمامًا كبيرًا في كل من المجتمعات العلمية والزراعية. تؤثر الطحالب و السيانوبكتريا على المحاصيل الزراعية لتعزيز نمو النباتات ونمو الشتلات وللمكافحة البيولوجية للأمراض البكتيرية والفطرية والنيماتودا وغزوات الحشرات. كما يمكنها أيضًا زيادة خصائص مقاومة النبات ضد الآفات والأمراض المختلفة. تسلط هذه المراجعة الضوء على الاستخدام المحتمل للطحالب و السيانوبكتريا في علم الزراعة، مع التركيز بشكل خاص على أنشطتها البيولوجية وتطبيقها المحتمل في التكنولوجيا الزراعية الحديثة كبديل مستدام محتمل لتحسين أداء المحاصيل والمرونة في مواجهة أمراض النبات

List of Abbreviation

Acibenzolar-S-methyl (ASM)

Acyl Homoserine Lactone (AHL)

biological control agents (BCA)

diacetylphloroglucinol (DAPG)

exopolysaccharides (EPS)

Fusarium oxysporum f. sp. *lycopersici* (FOL)

harmful algal blooms (HABs)

hydrogen cyanide (HCN)

Indole Acetic Acid (IAA)

induced systemic resistance (ISR)

integrated multitrophic aquaculture (IMTA)

jasmonic acid (JA)

methylisoborneol (MIB)

Mobility as a service (MaaS)

mycosporine amino acids (MAAs)

pathogen-associated molecular patterns (PAMP)

plant growth-promoting *rhizobacteria* (PGPR)

polyunsaturated fatty acids (PUFAs)

Quorum Quenching (QQ)

Quorum Sensing (QS)

reactive oxygen species (ROS)

salicylic acid (SA)

systemic acquired resistance (SAR)

ultraviolet (UV)

volatile organic compounds (VOCs)

γ-aminobutyric acid (GABA)

1. Introduction

Food security is increasingly threatened by phytopathogens, including bacteria, fungi, viruses, and nematodes, which can lead to significant crop yield losses and jeopardize the livelihoods of farmers, especially small-scale producers (Rizzo et al., 2021).

Today's sustainable agricultural farming is heavily dependent on chemical pesticides, excessive fertilizer and irrigation, and intensive use of tillages. This has resulted in several environmental and health problems. Where, the reliance on chemical pesticides and fungicides presents significant challenges, including environmental toxicity, adverse effects on non-target organisms, and the potential for pest resistance (Nikkanen et al., 2021).

In fact, sustainable agricultural practices can help in meeting the demands of a healthy environment and production of food crops. This technology use natural methods for plant pest management to conserve resources, such as soil and water, while preserving crop productivity, fostering resilience and self-regulating agricultural ecosystem (Koller et al. 2012).

In the endosphere, rhizosphere, and phyllosphere, a highly diverse group of distinct microorganisms have been observed associated with various plant species. These plant-associated microbes that produce metabolites may affect agricultural productivity in a neutral, positive, or negative way (Mendes et al. 2013). Since then, these microorganisms generated from plants have been used as biopesticides for crop protection strategy (Gwinn, 2018).

The use of biological control methods (including cyanobacteria and algae) offers several advantages; these organisms can enhance plant health by suppressing pathogens, improving nutrient uptake, and promoting overall plant growth without the harmful side effects associated with chemical treatments (Singh and Strong, 2016; Nikkanen et al., 2021).

Of all the options, cyanobacteria; prokaryotic microorganisms known also as "blue-green algae" and algae are unique bioactive organisms. These organisms are widely found in both terrestrial and aquatic habitats that scientists around the world are exploring very seriously. In the broadest sense, they are excellent phytopathogenic biocontrol agents. This long-standing current approach constrains the use of chemical pesticides has produced remarkable research material due to relatively cheap buying prices and environmental concerns. The European Directive 2009/128/EC also promotes the use of alternative materials for synthetic ones in the management of plant diseases.

The potential use of cyanobacteria, microalgae and seaweeds as biofertilizers, sources of bioactive substances like phycobiliproteins, and inducers of plant systemic resistance have been highlighted by recent studies on their application in agriculture (Hamed et al., 2018). In this context, cyanobacteria and algae have emerged as promising biostimulants and biocontrol agents. These microorganisms produce bioactive compounds that enhance plant growth and activate defense mechanisms against pests and diseases (Sharma et al., 2014; Manjunath et al., 2016; Sithole et al. 2023).

Furthermore, cyanobacteria and algae contribute to soil health by fixing nitrogen and improving nutrient availability, thereby promoting sustainable agricultural practices (Battacharyya et al., 2015; Sithole et al. 2023). Their diverse range of bioactive compounds offers multiple avenues for developing environmentally friendly pest management strategies (Berthon et al., 2021; Asimakis et al., 2022).

The eukaryotic microalgae and macroalgae (seaweeds), are the most varied, largest, and widely distributed group of organisms, varying in shape and size from unicellular to several meters' organisms. They are found specifically in fresh and marine water and "could have been the world's largest biomass. Research has shown that certain macroalgae, such as *Ulva fasciata*, exhibit effective nematicidal properties against plant-parasitic nematodes like *Meloidogyne incognita*, reducing egg hatching and juvenile mortality rates (Ghareeb et al., 2019).

Looking ahead, the integration of cyanobacteria and algae into agricultural practices presents promising opportunities for sustainable plant protection. However, challenges remain, including the need for further research to optimize their application, understand their ecological interactions, and develop effective methods for mass production and application (Nikkanen et al., 2021).

They also promote plant growth through the production of phytohormones, such as cytokinins and salicylic acid, which enhance root development and overall plant vigor (Toribio et al. 2021). Their application is environmentally friendly, as it minimizes soil and water pollution associated with conventional chemical treatments (Kumar and Verma 2013; Raymaekers et al. 2020).

Furthermore, algae and cyanobacteria can activate plant defense mechanisms, boosting resistance to various pathogens (Köhl et al. 2019). Additionally, they improve soil fertility by enhancing nutrient availability and promoting beneficial microbial communities (Renuka et al. 2018). Overall, integrating these biocontrol agents into agricultural practices represents a promising approach to sustainable disease management.

The current review provides a broad overview of recent findings regarding the application of cyanobacteria, microalgae and seaweeds for their plant bio-stimulant qualities as well as their bioprotective effect against bacterial and fungal phytopathogens. To properly and sustainably manage agricultural crops, we emphasize the importance of considering a number of elements, from the ways in which cyanobacteria improve plant growth to reducing plant diseases and modifying plant resistance.

2. Cyanobacteria

2.1. Description

Cyanobacteria, commonly known as "blue-green algae," are ancient photosynthetic prokaryotes that have existed for about 3.5 billion years (Schopf, 1993; Shestakov and Karbysheva, 2017). These microorganisms thrive in diverse environments, including freshwater, marine, and terrestrial habitats, and can endure extreme conditions such as high salinity and temperature (Whitton, 1992; Lang-Yona, 2018). They exhibit various forms, from unicellular to filamentous structures (Vidal et al. 2021; Dvořák et al. 2017; Uyeda et al. 2016) and play a vital role in photosynthesis by converting carbon dioxide into oxygen, utilizing chlorophyll-*a* and accessory pigments like phycobilins (Angermayr et al. 2009; Shestakov and Karbysheva, 2017; Humbert and Fastner, 2016; Barsanti and Gualtieri, 2014; Zakar et al. 2016).

Additionally, cyanobacteria produce a range of secondary metabolites, some of which have ecological significance and potential pharmaceutical applications (Chauvat and Cassier-Chauvat, 2021; Filatova et al. 2021). Their ability to fix nitrogen and contribute to primary production makes them crucial to Earth's ecosystems, although their blooms can lead to harmful algal blooms (HABs) that negatively impact water quality and aquatic life (Paerl and Huisman, 2009; Hallegraeff, 1993; Anderson et al. 2012) Furthermore, cyanobacteria are considered prospective biocontrol agents for various plants, though they have not received much attention (Pisciotta et al. 2010).

They are responsible for the oxygenic atmosphere we have today and have been identified in approximately 150 taxa. The characteristics of cyanobacteria are evident in some of the earliest fossils, dating back to 3.5 billion years (Hoekman et al. 2012). A theoretical framework illustrates their potential environmental and sustainable agricultural roles (Righini et al. 2022).

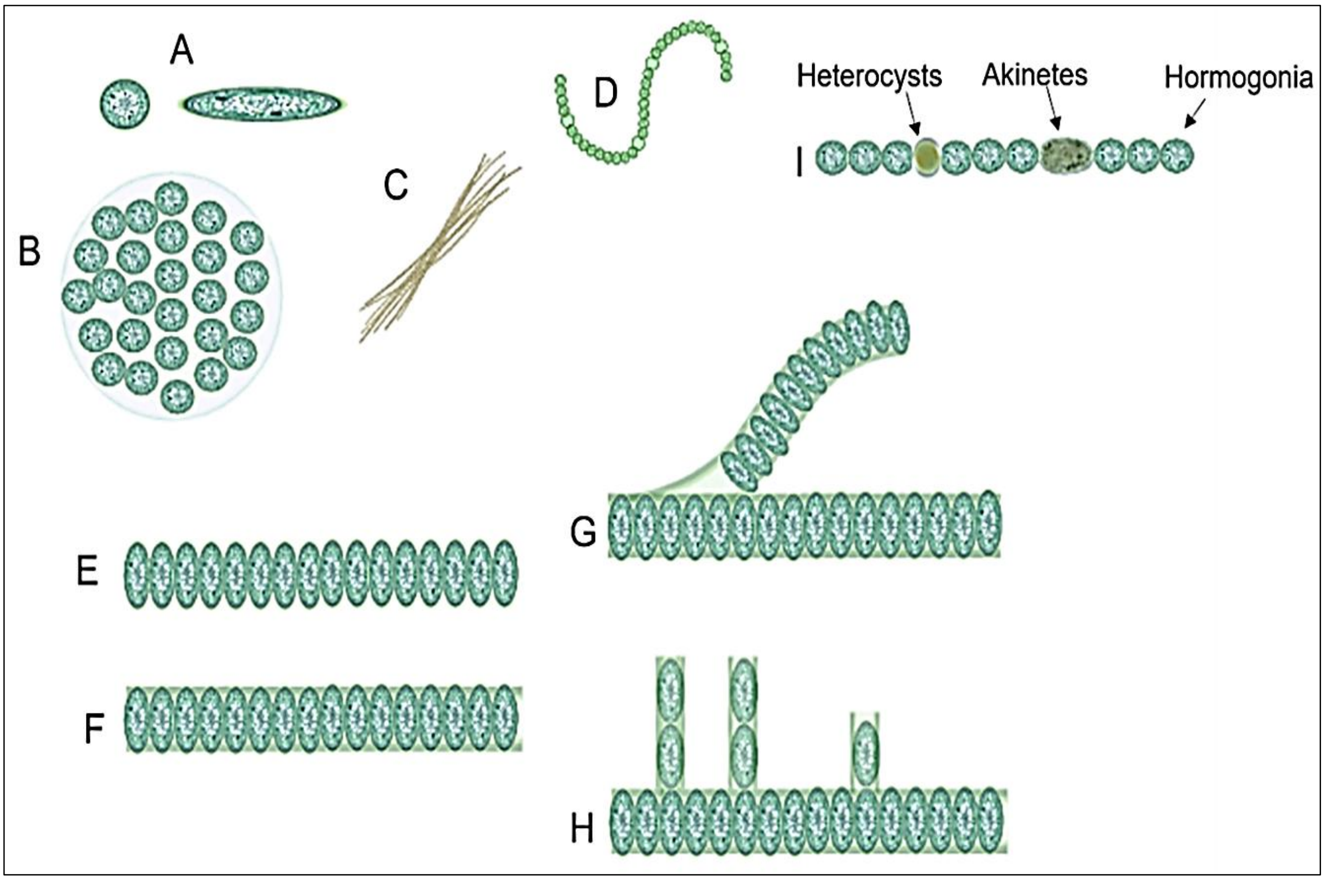


Fig.1. Different forms of cyanobacteria: (A) spherical and ovoid unicellular, (B) colonial, (C) filamentous, (D) spiral, (E) unsheathed trichome, (F) sheathed trichome, (G) false branching, (H) true branching, (I) different cell types in filamentous cyanobacteria. Most parts of this image were created with BioRender (Mehdizadeh and Peerhossaini 2022).

2.2. Distribution

Cyanobacteria are widely distributed in both aquatic and terrestrial environments. They thrive in freshwater systems, such as lakes, rivers, and ponds, as well as in marine environments, including coastal waters and open oceans (Pastrana et al. 2016). Additionally, they can be found in brackish waters like estuaries and salt marshes. On land, cyanobacteria inhabit moist soils, especially in arid and semi-arid regions, and are often integral components of lichen symbioses, enabling them to survive in harsh conditions (Romero et al. 2007; Jarvis et al. 2002; Shah et al.2021). Their ecological roles are significant, as they contribute to nitrogen fixation, enhancing soil fertility, and serve as primary producers in aquatic ecosystems, forming the foundation of the food web (Husaini and Neri 2016). Furthermore, cyanobacteria are recognized for their economic importance, being utilized as biofertilizers to improve soil quality and as potential sources for biofuel production.

2.3. Morphology

Cyanobacteria exhibit a diverse morphology that plays a vital role in their ecological adaptability and function. These prokaryotic organisms can vary in shape from spherical (cocci) and rod-shaped (bacilli) to filamentous forms, which may be unbranched or branched (Righini et al., 2022). Typically ranging from 0.5 to 10 micrometers in diameter, cyanobacteria often form colonies or long chains of cells (trichomes). They contain chlorophyll *a*, which gives them a green color, along with accessory pigments such as phycobiliproteins that can impart blue or red hues (Righini et al., 2022). Notably, some species develop specialized structures such as heterocysts for nitrogen fixation and akinetes for survival during adverse conditions. Additionally, cyanobacteria possess gas vesicles that facilitate buoyancy, allowing them to optimize their position in aquatic environments. Their mucilaginous sheath offers protection and aids in attachment to surfaces, further enhancing their resilience and ecological success (Righini et al., 2022).

Fig. 2. Diversity of Cyanobacteria and examples from each of the five divisions. Left column: heterocystous cyanobacteria. The top three belong to Division 4: *Anabaena sp.* with heterocysts (lighter cells) and akinetes (very large cells), *Calothrix sp.* with terminal heterocysts, and *Nodularia sp.* with intercalary heterocysts. Bottom: *Fischerella sp.* with true branching (Division 5). Middle column: non-heterocystous filamentous cyanobacteria (Division 3). From top to bottom: *Lyngbya sp.*, *Phormidium sp.*, *Spirulina sp.*, and *Trichodesmium sp.* Right column: unicellular cyanobacteria. Top three belong to Division 1: *Gloeocapsa sp.*, the colony-forming *Microcystis sp.*, and the tiny *Crocosphaera sp.* Bottom: *Dermocarpa sp.* with baeocytes (Division 2) (Stal, 2023).

2.4. Types

Cyanobacteria are diverse groups of photosynthetic microorganisms classified into several orders based on their morphology and ecological functions.

1. ***Oscillatoriales***

   - Characteristics: Filamentous structure with no true branching.
   - Examples: *Oscillatoria* and *Phormidium* (Hoekman et al. 2012).

2. ***Chroococcales***

   - Characteristics: Typically, unicellular or colonial; can form gelatinous colonies.
   - Examples: *Chroococcus* and *Microcystis* (Mendes et al. 2013).

3. ***Nostocales***

   - Characteristics: Known for heterocyst formation, important for nitrogen fixation.
   - Examples: *Nostoc* and *Anabaena* (El Sohaimy 2012).

4. ***Stigonematales***

   - Characteristics: Typically, filamentous and can be branched.
   - Examples: *Stigonema* and *Fischerella* (Schirrmeister et al. 2011).

5. ***Gloeobacterales***

   - Characteristics: Primitive group; lacks thylakoid membranes.
   - Example: *Gloeobacter* (Gupta et al. 2011).

2.5. Natural products

Cyanobacteria, particularly the genus *Leptolyngbya*, are rich sources of diverse natural products. Among these are *grassypeptolides* D and E (Haque et al. 2017; Vijayakumar and Menakha 2015), which exhibit cytotoxic activity against HeLa cells, and loggerpeptins A–C (Engene et al. 2013; Bertin et al. 2016; Castenholz 1988), known for their serine protease inhibition. The compound molassamide (Moss et al., 2018) shows promise by inhibiting porcine pancreatic elastase. Additionally, 2-hydroxyethyl-11-hydroxyhexadec-9-enoate (Leao et al. 2013) possesses antibacterial properties, while honaucins A–C (Yao et al. 2015; Yao et al.

2018; Medina et al. 2008) demonstrate anti-inflammatory effects and quorum-sensing inhibition.

In the macrolide category, *Leptolyngbya* produces leptolyngbyolides A–D (Thornburg et al. 2011; Harrigan et al. 1998; Pettit et al. 1989; Bates et al. 1997), which have moderate cytotoxicity and actin-depolymerizing activity, alongside palmyrolide A (Al-Awadhi et al. 2018), which inhibits calcium oscillations and blocks sodium channels. Another notable compound, phormidolide (Maneechote et al. 2017), is toxic to brine shrimp and has a complex stereochemistry.

The pyrones from this genus include kalkipyrone A (Sapkota et al. 2015) and kalkipyrone B (Cui et al. 2017), both of which are toxic to brine shrimp and exhibit cytotoxicity against human lung cancer cells. The yoshinones (Pereira et al. 2010; Williamson et al. 2002; Bertin et al. 2016) inhibits adipogenic differentiation, with yoshinone A showing significant activity. Additionally, crossbyanols A–D (Graber and Gerwick 1998; Inuzuka et al. 2014; Choi et al. 2010; Bhandari Neupane et al. 2019) are brominated polyphenolics with neurotoxic and antibiotic properties.

Leptolyngbya also produces leptazolines A–D (Hau et al. 2013; Snyder et al. 2016; Pettit et al. 1981; Adams et al. 2008), which modestly inhibit cancer cell growth, while toxins such as *saxitoxin* (Thornburg 2013) and microcystins (Williams et al. 2003; Li et al. 2020) present hepatotoxic and neurotoxic risks. Non-toxic metabolites like mycosporine amino acids (MAAs) and scytonemin (Gerwick et al. 2001; Li et al. 2020) provide UV protection and exhibit anti-inflammatory properties. Furthermore, various phenolic compounds, including gallic acid (Kwan et al. 2008; Li et al. 2020) and hydroxytyrosol (Gogineni and Hamann 2018), serve as natural antioxidants. Odorous metabolites such as *geosmin* (Wang et al. 2015) and 2-methylisoborneol (Schipper et al. 2020) contribute to off-flavors in water, while phycocyanin is a valuable light-harvesting pigment with potential biotechnological applications. Overall, the natural products from *Leptolyngbya* highlight the significant chemical diversity and biological activity of cyanobacteria.

2.6. Role of Cyanobacteria in Crop Protection

2.6.1. Biocontrol Agents:

Cyanobacteria can act as biocontrol agents by suppressing plant pathogens. They produce various antimicrobial substances that inhibit the growth of harmful fungi and bacteria (Górka et al., 2018).

2.6.2. Enhancement of Plant Defense Mechanisms.

Inoculation with cyanobacteria enhances the production of defense proteins and enzymes in plants, boosting their immune responses against pathogens (Prasanna et al., 2015).

2.6.3. Stress Alleviation:

Cyanobacteria help mitigate abiotic stresses such as drought and salinity, improving plant resilience by enhancing soil quality and nutrient availability (Singh et al., 2014).

2.6.4. Nutrient Supply:

They are capable of fixing atmospheric nitrogen, which enriches the soil and reduces the dependency on chemical fertilizers, contributing to healthier plant growth (H Osman et al., 2020).

2.6.5. Production of Bioactive Compounds:

Cyanobacteria produce bioactive metabolites, including phytohormones and antioxidants, which promote plant growth and stress resistance (Han et al., 2018).

3. Microalgae

3. 1. Description

Microalgae are diverse, photosynthetic microorganisms found in various aquatic environments, playing a crucial role in carbon fixation and significantly contributing to global oxygen production. Key types include green algae, and diatoms, each varying in size and function; for instance, diatoms have unique silica cell walls (Singh and Strong, 2016).

Beyond their ecological significance, microalgae are recognized for their applications in biofuels, nutraceuticals, and wastewater treatment, highlighting their potential in sustainable agriculture (Benson et al., 2014; Shah et al., 2021). They serve various agricultural purposes, including insecticides, herbicides, fungicides, biofertilizers, growth promoters, and resistance elicitors, often overlapping in function to provide multiple benefits. By stimulating soil microbial activity and enhancing nutrient availability, microalgae improve soil fertility, leading to healthier plants, increased crop yields, and better fruit quality (Renuka et al., 2018). This versatility positions microalgae as a vital component of sustainable agricultural practices.

Table 1. Description of all microalgae patents related to agriculture granted by EPO and WIPO (Barsanti et al. 2021).

Microalgae species	Product type	References
Microcystis aeruginosa	Insecticide	Astakhov et al. (2005)
Oscillatoria sp.	Herbicide	Lee (2016)
Amphidium carterae, Prymnesium parvum, Phaeodactylum tricornutum	Fungicide	Thiebeauld de la Crouee, O. and Thomas (2016)
Chlorella, Aurantiochytrium acetophilum, Galdieria, Scenedesmus, Haematococcus, Isochrysis, Spirulina	Post-harvest	Carney and Michael (2017)
Chlorella spp.	Growth promoter	Cheng et al. (2017)
Chlororella sp., *Paeodactylium sp.*	Lawn protector	Baek (2017)
Clorella sp.	Resistance elicitor	Moo and Min (2019)
Chlorella, Aurantiochytrium acetophilum, Galdieria, Scenedesmus, Haematococcus, Isochrysis, Spirulina	Fungicide	Carney et al. (2019)
Chlorella, Aurantiochytrium acetophilum, Galdieria, Scenedesmus, Haematococcus, Isochrysis, Spirulina	Post-harvest	Carney et al. (2018)
Arthrospira sp. (Spirulina sp.)	Biofertilizer	Mógor et al. (2019)

3.2. Distribution

Microalgae distribution in polar marine environments is influenced by several key environmental factors. Light availability is crucial for photosynthesis, significantly affecting their presence in habitats like seawater, sea ice, and snow-covered surfaces (Hopes et al. 2017). Additionally, variations in salinity and temperature impact growth; while some species tolerate high salinity, others are more sensitive, shaping their distribution patterns (Palmisano et al. 1987; Lauritano et al. 2020).

Nutrient levels, especially micronutrients like iron, are critical, as seen in the Southern Ocean, which supports phytoplankton blooms under optimal conditions despite being classified as high-nutrient, low-chlorophyll (Duprat et al. 2020). Antarctica exhibits greater species endemism compared to the Arctic, highlighting unique ecological dynamics (Mock and Thomas 2008; Lauritano et al. 2020).

Furthermore, ecological interactions between microalgae and heterotrophic bacteria influence community dynamics (Landa et al. 2016). Beyond marine environments, microalgae thrive in freshwater habitats such as rivers, lakes, and ponds, and they can adapt to extreme conditions, including saline and alkaline soils and wastewater. This adaptability enhances their ecological significance, allowing them to contribute significantly to carbon fixation and primary production across diverse ecosystems (Singh et al., 2020; Zada et al., 2021).

3.3. Morphology

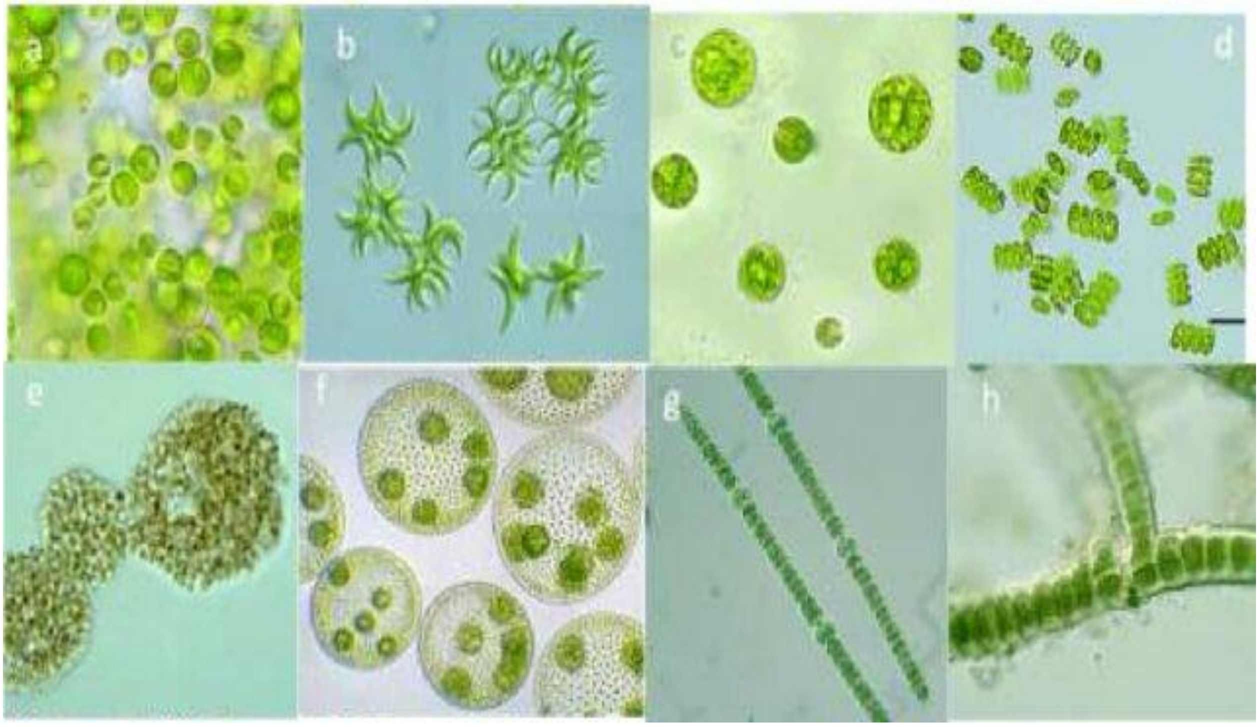


Fig.3. Main morphological forms of microalgae. Unicellular non-motile (a) *Chlorella* and (b) *Selenastrum*; Unicellular motile (c) *Chlamydomonas*; Small colonies (d) *Scenedesmus*; Large irregular shape colonies (e) *Microcystis*; Globular shape colonies (f) *Volvox*; Unbranched ilaments (g) *Anabaena* and branched ilaments (h) *Stigonema*. Images Source: (Baker et al., 2012).

The morphology of microalgae is essential for understanding their characteristics and potential applications. *Chlorella vulgaris* exhibits a weakly ellipsoidal shape, measuring between 1.5 to 2.0 µm and is characterized by its green or dark green color, along with cup-shaped chloroplasts; notably, it lacks flagella (Fig. 4).

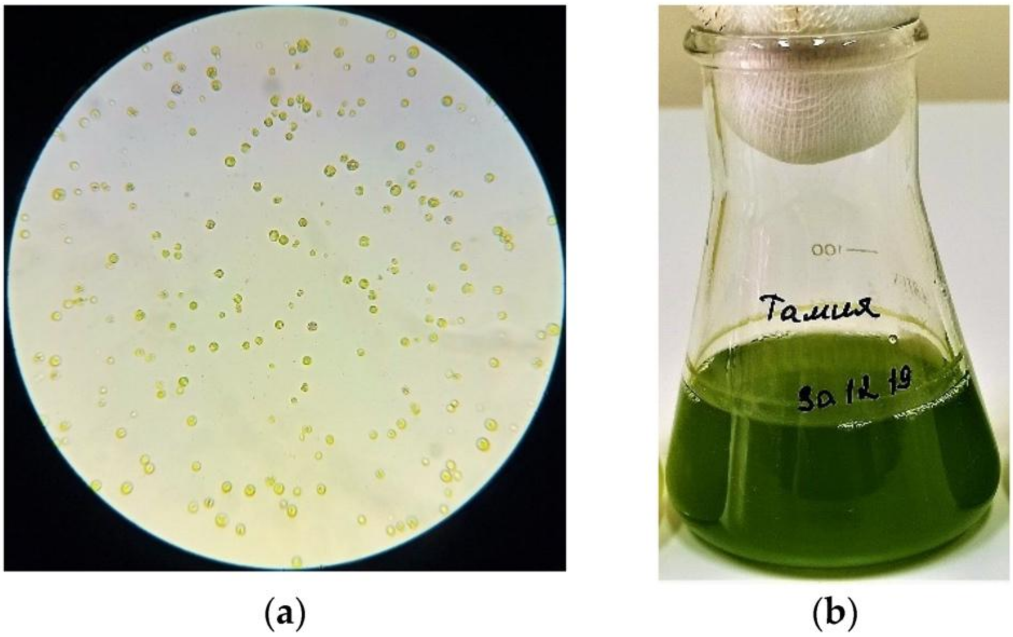
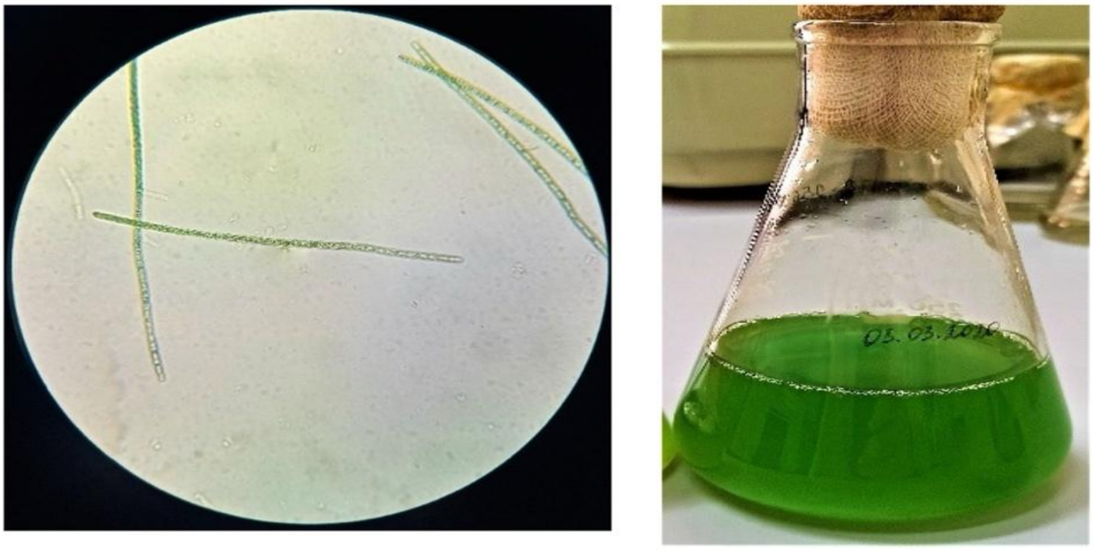


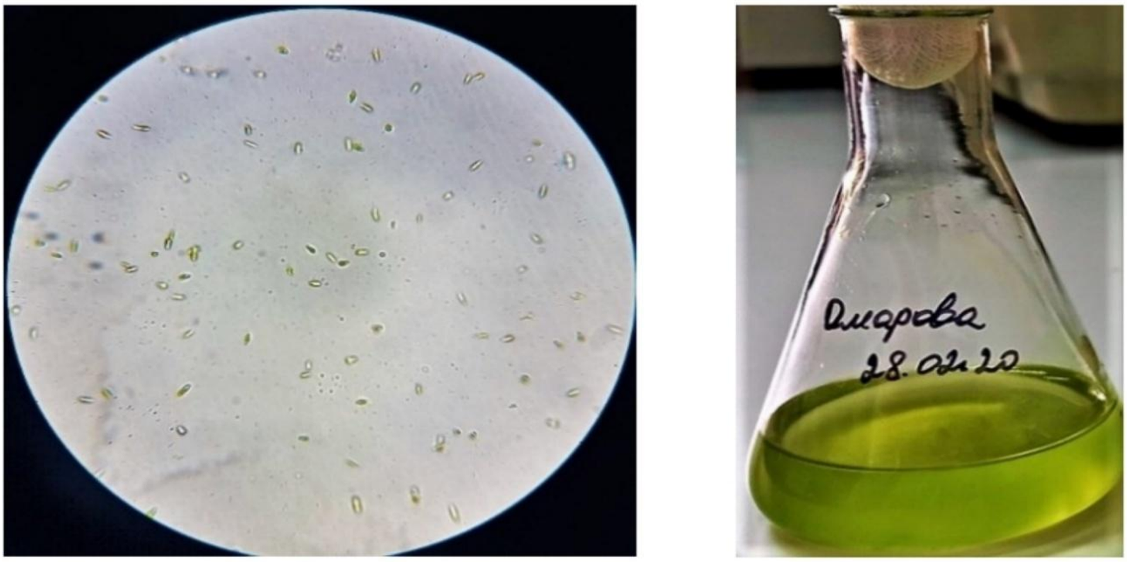
Fig. 4. The results of studying the morphological features of the microalgae *Chlorella vulgaris* and their suspensions: (a) Cells under a microscope; (b) The suspension's appearance (Dolganyuk et al. 2020).

In contrast, *Arthrospira platensis* presents poorly coiled trichomes, with cell lengths ranging from 8.0 to 10.0 µm and widths between 2.0 to 4.5 µm, maintaining a similar green hue (Fig. 5)



(a) (b)

Fig. 5. The results of studying the morphological features of the microalgae *Arthrospira platensis* and their suspensions: (a) Cells under a microscope; (b) The suspension’s appearance (Dolganyuk et al. 2020).



(a) (b)

Fig. 6. Morphological features of the microalgae *Dunaliella salina* and their suspensions: (a) Cells under a microscope; (b) The suspension’s appearance (Dolganyuk et al. 2020).

Lastly, *Dunaliella salina* features a wide-oval shape, with sizes varying from 7.5 to 10.5 µm, displaying a green color and possessing flagella (Fig. 6). These morphological traits play a vital role in assessing biomass accumulation and the cultivation potential of each microalgal species.

3. 4. Types

1. Green Algae (*Chlorophyceae*)

- Characteristics: High lipid content, fast growth rates, often found in freshwater environments.

- Examples:

- *Chlorella vulgaris*: Known for its high lipid and protein content, widely used in biodiesel production. (Al-lwayzy et al. 2014; Cho et al. 2016; Gui et al. 2021; Nascimento et al. 2013; Wu and Miao 2014; Xu et al. 2013; Hegel et al. 2017; Ma et al. 2014).

- *Scenedesmus*: Noted for high biomass yield and lipid productivity (Wu and Miao 2014; Yu et al. 2019).

- *Botryococcus braunii*: Produces large amounts of hydrocarbons (Wu and Miao 2014; Blifernez-Klassen et al. 2018; Fang et al. 2018).

- Usage: Commonly used for biodiesel production due to high lipid accumulation (Wu and Miao 2014; Yu et al. 2019).

2. *Euglenophyta* (*Euglenoids*)

- Characteristics: Mixotrophic; can photosynthesize or absorb nutrients from the environment.

- Examples:

- *Euglena gracilis*: Known for high lipid content and adaptability.

- Usage: Recognized for its potential in biodiesel production due to significant lipid accumulation (Chong et al. 2022).

3.5. Natural products their role in crop protection

Natural products derived from microalgae play a crucial role in crop protection by providing various bioactive compounds that enhance plant resilience against pathogens and environmental stresses. These compounds, including phenolic acids, terpenoids, and polysaccharides, exhibit antimicrobial properties, effectively inhibiting the growth of harmful microorganisms such as bacteria and fungi (Singh et al. 2017; Pan et al. 2019; Esquivel-Hernández et al. 2017; Foo et al. 2017; Goiris et al.2012; Khoddami et al. 2013; Michalak et al. 2017; Oksana et al. 2012).

In addition to acting as natural biopesticides, these metabolites can stimulate the plant's own defense mechanisms, enhancing its resistance to diseases [Singh et al. 2017; Pan et al. 2019; Pavela and Benelli 2016). Microalgae also contribute to soil health by improving fertility and aiding in the bioremediation of contaminated soils, which supports overall plant vigor (Chiaiese et al. 2018; Dmytryk and Chojnacka 2018; Górka et al 2018) [Fig. 7].

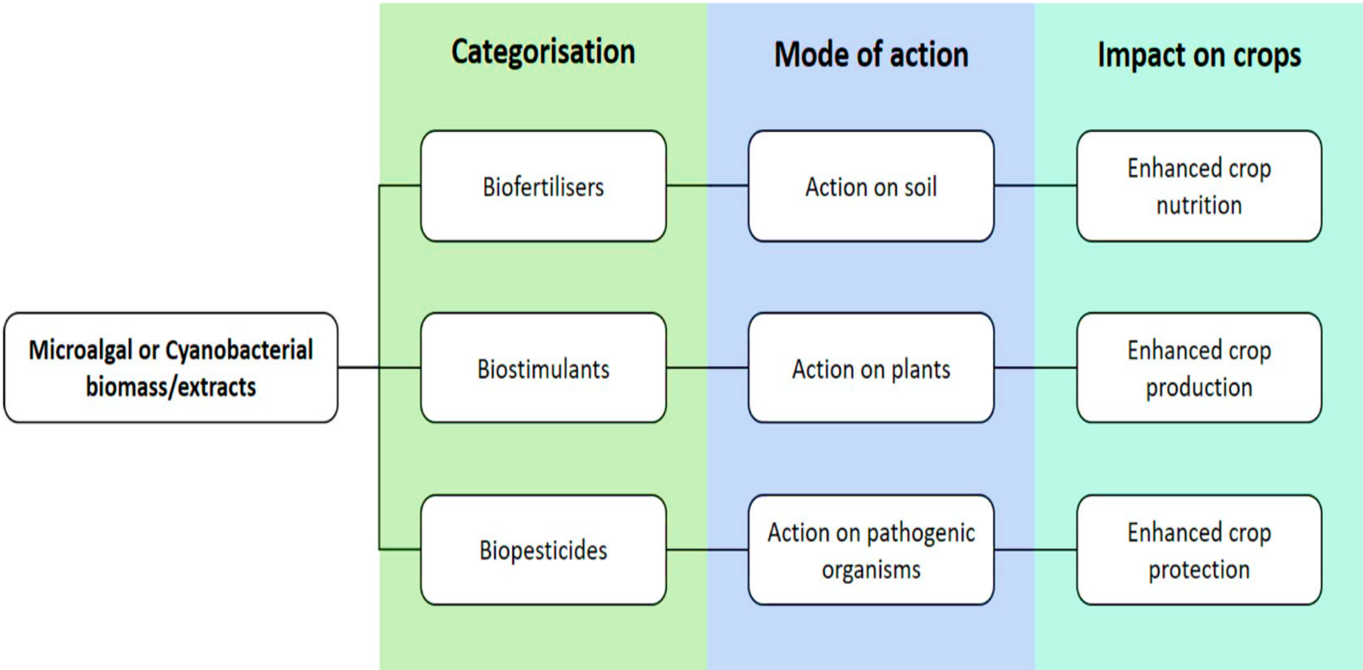


Fig. 7. Categorization of the main activities attributed to algal/cyanobacterial biomass and extracts in crops' production. (Gonçalves, 2021).

Moreover, the phytohormones produced by microalgae can regulate physiological processes in plants, promoting growth and increasing stress tolerance [Singh et al. 2017, Ronga et al. 2019; Han et al. 2018; Lu and Xu 2015). [Table 2].

This multifaceted approach highlights the potential of microalgae as sustainable solutions in agricultural practices, reducing reliance on synthetic chemicals while fostering healthier crop production.

Table 2. Microalgal and cyanobacterial metabolites with potential interest for agriculture (Gonçalves, 2021).

Metabolites	**Examples**	**Microalgal/Cyanobacterial Sources**	**Biological Activity**	**Role in Agriculture**	**Refs.**
Phenolic compounds	Polyphenols; phenolic acids; flavonoids; phenylpropanoids	*Botryococcus braunii*; *Chaetoceros calcitrans*; *Chlorella vulgaris*; *Isochrysis galbana*; *Isochrysis* sp.; *Neochloris oleoabundans*; *Odontella sinensis*; *Phaeodactylum tricornutum*; *Saccharina japonica*; *Skeletonema costatum*; *Tetraselmis suecica*	Antibacterial; antioxidant; antifungal	Crops' protection against pathogens or other biotic and abiotic stress conditions	(Singh et al. 2017; Pan et al. 2019; Esquivel-Hernández et al. 2017; Foo et al. 2017; Goiris et al.2012; Khoddami et al. 2013; Michalak et al. 2017; Oksana et al. 2012)
Terpenoids	Hemiterpenes; monoterpenes; sesquiterpenes; diterpenes; triterpenes; polyterpenes	*Chondrococcus hornemanni*; *Hypnea pannosa*; *Oscillatoria perornata*; *Planktothricoids raciborskii*; *Plocamium cornutum*; *Plocamium leptophyllum*; *Portieria hornemann*; *Pseudanabaena articulate*; *Pseudanabaena* sp.; *Sphaerococcus coronopifolius*; *Synechocystis* sp.; *Thermosynechococcus elongatus*	Antibacterial; anticarcinogenic; antioxidant	Crops' protection against bacteria, insects and other organisms Stimulation of preliminary growth and development of plants Attraction of pollinators	(Singh et al. 2017; Pan et al. 2019; Betterle and Melis 2019; Awasthi et al. 2018; Gershenzon and Dudareva 2007; Pattanaik and Lindberg 2015; Pavela and Benelli 2016; Rodriguez-Garcia et al. 2017; Wei et al. 2019)
Free fatty acids	Saturated and unsaturated fatty acids	*Anabaena*; *Chlorella*; *Dunaliella*; *Nannochloropsis*; *Porphyridium*; *Scenedesmus*; *Spirulina*	Antibiotic; anticarcinogenic; antifungal; antioxidant; antiviral	Crops' protection against pathogens or other biotic and abiotic stress conditions	(Singh et al. 2017; Pan et al. 2019; Demirbas, and Demirbas 2011; Desbois and Smith 2010; El-Baz et al. 2013; Feller et al. 2018; Lam and Lee 2012)

Polysaccharides	Extracellular polysaccharides; structural polysaccharides; energy-storage polysaccharides	*Aphanothece*; *Arthrospira*; *Chlamydomonas*; *Chlorella*; *Cylindrotheca*; *Dunaliella*; *Navicula;* *Nostoc*; *Phaeodactylum*; *Porphyridium*; *Rhodella*; *Scytonema*	Antibacterial; anticancer; anticoagulant; anti-inflammatory; antioxidant	Improvement of soil quality Plant growth stimulation Crops' protection against biotic and abiotic stress conditions	(Singh et al. 2017; Pan et al. 2019; El Arroussi et al. 2018; Campos et al. 2015; Chanda et al. 2019; Delattre et al. 2016; Dvir t al. 2009; Elarroussia et al. 2016; Farid et al. 2019; González et al. 2013; Guilherme et al. 2015; Guzmán et al. 2003; Rechter et al. 2006; Usman et al. 2017; Vera et al. 2011)
Carotenoids	Alpha-carotene; beta-carotene; lutein; lycopene; astaxanthin; zeaxanthin	*Chlorella protothecoides*; *Chlorella pyrenoidosa*; *Chlorella zofingiensis*; *Dunaliella salina*; *Haematococcus pluvialis*; *Muriellopsis* sp.; *Phaeodactylum tricornutum*; *Spirulina* sp.	Anticancer; anti-inflammatory; antioxidant	Soil bioremediation and fertilisation Crops' protection against bacteria, insects and other biotic and abiotic stress conditions Crops' fortification	(Pan et al. 2019; Cezare-Gomes et al. 2019; Galasso et al. 2017; Guedes et al. 2011; Han et al. 2016; Rajesh et al. 2017; Raposo et al. 2015; Sakamoto et al. 2017)
Phytohormones	Auxins; abscisic acid; cytokinins; ethylene; gibberellins	*Arthrospira*; *Chlamydomonas*; *Chlorella*; *Phormidium*; *Protococcus*; *Scenedesmus*	Chemical messengers	Plant growth stimulation Regulation of cellular activities in crops Crops' response to stress conditions	(Singh et al. 2017; Ronga et al. 2019; Pan et al. 2019; Han et al. 2018; Lu and Xu 2015; Ördög et al. 2004)

3. Macroalgae (Seaweeds)

3.1. Description

Macroalgae, commonly known as seaweeds, are large marine algae that serve as a nutritious and sustainable alternative to animal-based proteins. They are categorized into three primary groups: green algae, brown algae, and red algae, each distinguished by their pigmentation and environmental preferences (Cherry et al., 2019). Seaweeds are rich in essential nutrients, including vitamins, minerals, and dietary fibers, and can have protein content as high as 47% by dry weight (Fleurence et al., 2012; Embling et al. 2022). They are low in calories and fats, making them a healthy dietary option (Mahadevan, 2015). Additionally, seaweed cultivation is environmentally sustainable, requiring no fertilizers or freshwater, which contributes to their appeal as a food source (Rust et al., 2020). Despite their numerous benefits, the consumption of seaweed remains low in many Western countries, indicating a need for further research to enhance consumer acceptance and integration into modern diets (Birch et al., 2019).

3.2. Distribution

Marine macroalgae, commonly known as seaweeds, are a diverse group of photosynthetic organisms found in various marine environments, spanning from polar regions to the tropics. They occupy approximately 25% of the world's coastlines, particularly in temperate seas where kelp and fucoid species dominate (Wernberg et al., 2019). The distribution of seaweed is influenced by several factors, including temperature, ocean currents, and light availability (van den Hoek, 1984; Aguirre et al., 2000; Hanley et al. 2024). Red algae tend to thrive in deeper waters due to their tolerance of low light, while green algae are highly adaptable and can be found in a variety of habitats, including intertidal zones (Pessarrodona et al., 2022). Brown algae, especially kelps, are prevalent in temperate and polar waters, where they play critical roles as primary producers, providing essential habitats and food for numerous marine organisms (Dayton, 1985; Krumhansl et al., 2016). Overall, the distribution of macroalgae is shaped by a combination of ecological interactions and environmental conditions, making them vital components of marine ecosystems.

Fig.8. A montage illustrates the global taxonomic and morphological diversity of marine macroalgae. (A) *Hormosira banksia* – Fucales (Phaeophyta) – Hobart, Tasmania; (B) *Nereocystis luetkeana* – Laminariales (Phaeophyta) – Bandon Bay, Oregon, USA; (C) *Corallina officinalis* – Corallinales (Rhodophyta) – Sennen Cove, UK; (D) *Chondrus crispus* – Gigartinales (Rhodophyta) – Sennen Cove, UK; (E) *Ecklonia maxima* – Laminariales (Phaeophyta) – Cape Town, South Africa; (F) *Ascophyllum nodosum* – Fucales (Phaeophyta) – Wembury, UK (algae growing on concrete defence blocks); (G) *Halimeda spp*. – Bryopsidales (Chlorophyta) – East Kalimantan, Indonesia (algae growing on mangrove roots); (H) *Ulva latuca* – Ulvales (Chlorophyta) Plymouth Breakwater, UK. All photos by the authors. (Hanley et al. 2024)

3.3. Morphology

Macroalgae, or seaweeds, possess diverse morphological characteristics essential for identification and classification. Their structure is defined by the thallus, which is not differentiated into true stems, leaves, or roots. Thalli can be erect or prostrate, exhibiting forms such as filamentous, massive, hollow tubes, sheets, and vesicular types. The consistency of macroalgae varies significantly, ranging from cartilaginous and leathery to mucilaginous and calcareous, which reflects their adaptation to different marine environments. Growth patterns include apical, diffuse, and marginal growth, and the morphology of thalli is influenced by external factors such as wave exposure and light availability, leading to variations among individuals of the same species (Pereira, 2021).

The external environmental conditions in which they develop can intensify these differences, and they can be particularly noticeable in populations of the same species, such as *Chondrus crispus* and *C. crispus* var. filiformis (Fig. 9), which are prevalent along North Atlantic European shores in coastal regions with high wave exposure.

Fig. 9. Macroalgae collected from the Antarctic Peninsula, with information on their distributions given in parenthesis. (**a**) *Acrosiphonia arcta* (Dillwyn) Gain (cosmopolitan); (**b**) *Adenocystis* sp. (most likely endemic); (**c**) *Adenocystis utricularis* (Bory de Saint-Vicent) Skottsberg (Australia, New Zealand and Antarctica); (**d**) *Monostroma hariotii* Gain (Antarctic and Subantartic islands); (**e**) *Palmaria decipiens* RW Ricker (Antarctic and Subantarctic islands); (**f**) *Ulva intestinalis* Linnaeus (cosmopolitan); (**g**) *Phaeurus antarcticus* Skottsberg (Antarctic and the Subantarctic islands); (**h**) *Desmarestia menziesii* J Agardh (Antarctic and the Subantarctic islands). Bars represent 1 cm (Godinho et al. 2013).

3. 4. Types

Macroalgae, commonly known as seaweeds, are classified into three main groups based on their pigmentation and other biological characteristics:

1. Green Macroalgae (*Chlorophyta*):

- Characteristics: Contain chlorophyll, giving them a green color. They are primarily found in shallow waters and have a diverse range of forms, from filamentous to leafy (Leal et al. 2013; Moreira et al. 2022).
- Examples: *Ulva* (sea lettuce), *Monostroma*, and *Caulerpa*.

2. Red Macroalgae (*Rhodophyta*):

- Characteristics: Contain phycoerythrin, which gives them a red color. They are often found in deeper waters and can be involved in the formation of coral reefs (Leal et al. 2013; Moreira et al. 2022).
- Examples: *Porphyra* (nori), *Gracilaria*, and *Chondrus crispus* (Irish moss).

3. Brown Macroalgae (*Ochrophyta*):

- Characteristics: Contain fucoxanthin, resulting in a brown or olive color. They are typically larger and include some of the largest seaweeds, often forming underwater forests (Leal et al. 2013; Moreira et al. 2022).
- Examples: *Laminaria* (kelp), *Sargassum*, and *Fucus*.

These groups differ in their ecological roles, life cycles, and uses in various industries, including food, pharmaceuticals, and biofuels.

3. 5. Natural products their role in crop protection

Natural products derived from macroalgae (seaweed) play a crucial role in crop protection by enhancing plant immunity and providing resistance against a variety of pathogens. These seaweed-derived compounds, known as phyco-elicitors, include polysaccharides such as alginates, carrageenans, and laminarins. They function by activating plant defence mechanisms through the recognition of pathogen-associated molecular patterns (PAMPs), which triggers systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways. This recognition leads to the expression of defense-related genes and the production of enzymes involved in fortifying plants against infections, thereby reducing disease incidence and severity (Shukla et al.2021).

For instance, studies have shown that alginates can elicit resistance in plants by regulating the expression of defense-responsive genes and enhancing the activity of antioxidative enzymes (Dey et al., 2019). Similarly, carrageenans have been demonstrated to modulate different defence pathways, including salicylic acid (SA) and jasmonic acid (JA) signaling, which play pivotal roles in plant immunity (Sangha et al., 2015). The effectiveness of various seaweed extracts against specific pathogens is summarized in Table 3

.Table 3. Seaweed-derived elicitors (phyco-elicitors) and their roles in the defence mechanism of plants (Shukla et al., 2021).

Elicitors	**Source**	**Mode of Application**	**Mode of Action**	**Reference**
Sodium alginate	Commercial	Foliar spray	Elicited resistance in tomato against *Alternaria solani* by regulating expression of defense responsive genes and antioxidative enzymes	(Dey et al.2019).
Alginate	*Fucus spiralis, Bifurcaria bifurcata*	Root soaking	Stimulation of natural defense of the roots of date palm	Bouissil et al. 2020)
Alginate-derived oligosaccharides	Kelp	Cotyledon assay	Stimulated the accumulation of phytoalexin and phenylalanine ammonia lyase (PAL) in soybean cotyledon	(An et al 2009)
Alginate oligosaccharides	Source unknown	Root drench	Elicited disease resistance against *Pseudomonas syringae* by inducing salicylic acid (SA)-defense pathway	(Zhang et al. 2019)
Laminarin	*Laminaria digitata*	Foliar spray	Primed grapevine against *Plasmopara viticola* by inducing SA and ROS-dependent pathways	(Gauthier et al. 2014)
Laminarin	*L. digitata*	Foliar spray	Reduced *Botrytis cinerea, Sphaerotheca macularis and Mycosphaerella fragariae* infection in strawberry	(Meszka and Bielenin 2011)
Laminarin	*L. digitata*	Foliar spray	Increased protection of grapevine against *B. cinerea* and *P. viticola* by inducing expression of defense-related gene, accumulation of phytoalexins, chitinase, and β-1,3-glucanase activities	(Aziz et al. 2003)
Laminarin	*L. digitata*	Leaf infiltration	Strong reduction in soft rot disease caused by *Erwinia carotovora* in tobacco	(Klarzynski et al. 2000)
Laminarin	*L. digitata*	Leaf infiltration	Induced SA dependent defense signalling pathway in *Arabidopsis* and tobacco	(Meénard et al. 2004)
Laminarin	*L. digitata*	Leaf infiltration	Elicited defense response against tobacco mosaic virus (TMV) in tobacco by regulating the expression of genes involved in phenylpropanoid pathway	(Ménard et al. 2005)
Laminarin	*L. digitata*	Foliar spray	Reduced infection of powdery mildew in grapes	(Pugliese et al. 2018)
Laminarin	*L. digitata*	Foliar spray	Induced defense response in *Vitis vinifera* against *P. viticola* by regulating hypersensitive response and expression of defense-responsive genes	(Trouvelot et al. 2008)
Laminarin	*L. digitata*	Foliar spray	Elicited defense responses in tea against the piercing herbivore *Empoasca (Matsumurasca) onukii*	(Xin et al.2019)

Laminarin	*L. digitata*	Foliar spray	Increased elicitation of defense response against downy mildew in grapevine	(Paris et al. 2016)
Laminarin	*L. digitata*	Leaf disc assay	Elicited defense responses in leaves of grapevine against *P. viticola*	(Adrian et al. 2017)
Iodus 40 (Laminarin)	*L. digitata*	Foliar spray	Improved defense response in wheat against powdery mildew infection	(Renard-Merlier et al. 2007)
λ-carrageenan	Commercial †	Foliar spray	Suppressed Tomato Chlorotic Dwarf Viroid replication by inducing the expression of the jasmonic acid (JA)-responsive gene	(Sangha et al. 2015)
l-carrageenan	Commercial †	Foliar spray	Induced defense response against *Trichoplusia ni* by modulating glucosinolate metabolism and expression of defense-responsive gene	(Sangha et al. 2011)
λ-carrageenan	Commercial †	Foliar spray	Elicited defense response in *Arabidopsis* against *Sclerotinia scleortiorum* by SA-independent defense signalling pathway	(Sangha et al. 2010)
λ-carrageenan	*Acanthophora spicifera*	Foliar spray	Elicited *Hevea brasiliensis*defense against *Phytophthora palmivora* by inducing the SA-dependent defense signalling pathway	(Pettongkhao et al. 2019)
λ-carrageenan	*Gigartina acicularis, Gigartina pistillata*	Leaf infiltration	Induced resistance in *Nicotiana tabacum* against *Phytophthora parasitica* by regulating the expression of defense-related genes	(Mercier et al. 2001)
λ-carrageenan	Commercial †	Foliar spray	Elicited SA- and JA- dependent signalling pathways in wheat against Septoria tritici blotch caused by *Zymoseptoria tritici*	(Le Mire et al. 2019)
κ-carrageenan	*Kappaphycus alvarezii*	Foliar spray	Reduced anthracnose disease caused by *Colletotrichum gloeosporioides* in *Capsicum annuum* by inducing the defense-related antioxidant enzyme peroxidase	(Mani and Nagarathnam 2018)
κ-carrageenan	*Hypnea musciformis*	Leaf infiltration	Activated SA- and jasmonic acid/ethylene (JA/ET)- defense signalling pathways and confers resistance against TMV	(Ghannam et al. 2013)
Oligo-carrageenan	*TMV, B. cinerea Pectobacterium carotovorum*	Foliar spray	Reduced progression of pathogen in tobacco plants by inducing synthesis of secondary metabolites	(Vera et al. 2012)
Alginate, carrageenan, laminarin Ulvan	Commercial † *Ulva Lactuca*	In vitro assay	Ulvan and alginates reduced verticillium wilt of *Olea europaea* caused by *Verticillium dahliae* by stimulating phenolic metabolism	(Ben Salah et al. 2018)
Ulvan	*U. Lactuca*	Foliar spray	Elicited defense response against *Alternaria brassicicola* and *Colletotrichum higginsianum*	(de Freitas et al. 2015)

Ulvan	*U. Lactuca*	Foliar spray	Controlled *Fusarium* wilt in *Phaseolus vulgaris* caused by *Fusarium oxysporum*	(de Borba et al. 2019)
Ulvan	*Ulva fasciata*	Foliar spray	Elicited resistance against powdery mildew in wheat and barley	(Paulert et al. 2010)
Ulvan	*U. fasciata*	Foliar spray	Induced resistance in *P. vulgaris* against anthracnose disease caused by *Colletotrichum lindemuthianum*	(Paulert et al. 2009)
Ulvan	*Ulva armoricana*	Leaf infiltration, Foliar spray	Activated plant immunity through JA-signalling pathway	(Jaulneau et al. 2010)
Ulvan	*Ulva* sp.	In vitro assay	Reduced Anthracnose disease caused by *C. gloeosporioides* in papaya by inducing antioxidant defense enzyme activity	(Chiquito-Contreras et al. 2019)
Ulvan	*U. fasciata*	Foliar spray	Elicited the defense in *P. vulgaris* against bean rust and angular leaf spot	(Delgado et al. 2013)
Ulvan	*U. fasciata*	Foliar spray	Increased defense responses in *P. vulgaris*against Anthracnose disease caused by *C. lindemuthianum*	(de Freitas and Stadnik 2012)
Ulvan	*U. fasciata*	Foliar spray	Stimulated resistance in *Arabidopsis* against *A. brassicicola* by increasing the activity of defense related antioxidant enzymes	(de Freitas and Stadnik 2015)
Fucan	*Pelvetia canaliculata*	Leaf infiltration	Stimulated defense responses in tobacco against tobacco mosaic virus	(Klarzynski et al. 2003)
Oligoulvans, oligoglucuronans	*U. Lactuca*	Leaf infiltration	Reduced occurrence of wilt caused by *F. oxysporum* in tomato by inducing SA-dependent systemic acquired resistance	(El Modafar et al. 2012)
Glucuronan, oligoglucuronans	*U. Lactuca*	In vitro assay	Reduced growth of *Penicillium expansum* and *B. cinerea* on apple fruit by modulating the generation of ROS and defense-related enzymes	(Abouraïcha et al. 2017)
oligo-sulphated-galactan	*Schyzimenia binderi*	Foliar spray	Enhanced activity of defense-related enzymes in tobacco against TMV infection	(Vera et al.2011)
Eckol	*Ecklonia maxima*	Foliar spray	Increased aphid resistance in cabbage	(Rengasamy et al. 2016)

† The bioactive compounds used in these reports were purchased from commercial companies. The source of bioactive compounds was not mentioned

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As concerns over the extensive use of synthetic pesticides grow, these natural alternatives provide an eco-friendly solution for sustainable agriculture, significantly reducing reliance on chemical inputs while promoting overall crop health and resilience. (Table 4) outlines the bioactive compounds found in various seaweed species and their respective effects on plant health

Table 4. Roles of different extracts from various seaweeds in inducing disease resistance in different plants (Shukla et al. 2021).

Extract	Source	Type of Extract	Mode of Application	Crop	Causal Organism	Disease	Function	References
Algamare®	*Ascophyllum nodosum*	Alkaline	Foliar spray	*Prunus salicina*	*Monilinia fructicola*	Brown rot	Reduced the incidence and severity of brown rot	(Viencz et al. 2020)
Dalgin Active®	*A. nodosum*	Aqueous	Foliar spray	*Triticum aestivum, Triticum durum*	*Zymoseptoria tritici*	*Septoria tritici*blotch	Improved defense response by inducing expression of PR-proteins, antioxidant metabolism, and phenylpropanoid and octadecanoid pathways	(Somai-Jemmali et al. 2020)
Dalgin®	*A. nodosum*	Aqueous	Root drench	*Solanum lycopersicum*	*Phytophthora capsici*	Damping-off	Induced systemic defense response by eliciting the expression of defense-related genes or proteins	(Panjehkeh and Abkhoo 2016)
Marmarine®	*A. nodosum*	Alkaline	Foliar spray, root drench	*Cucumis sativus*	*Phytophthora melonis*	Damping-off	Control the progression of disease by inducing defense related enzymes	(Abkhoo and Sabbagh 2016)
Maxicrop Original®	*A. nodosum*	Alkaline	In vivo assay	*Arabidopsis*	*Meloidogyne javanica*	Root-knot	Diminished population of females of *M. javanica* on treated plants	(Wu et al. 1998)
Maxicrop Triple®	*A. nodosum*	Alkaline	Foliar spray	*Fragaria × ananassa*	*Tetranychus urticae*	-	Control growth of the pest on treated plants	(Hankins and Hockey 1990)
Stimplex®(Acadian Seaplants)	*A. nodosum*	Alkaline	Foliar spray, root drench	*C. sativus*	*Alternaria cucumerinum, Didymella*	*Alternaria*blight, Gummy stem blight, *Fusariu*	Protect the plants by inducing the activity different-related	(Jayaraman et al. 2011)

					applanata, Fusarium oxysporum, Botrytis cinerea	*m*root and stem rot, *Botrytis*blight	enzymes and higher accumulation of secondary metabolites	
Stimplex®	*A. nodosum*	Alkaline	Foliar spray	*S. lycopersicum, Capsicum annuum*	*Xanthomonas campestris* pv. *Vesicatoria, Alternaria solani*	bacterial spot, early blight	Reduced disease susceptibility by inducing the expression of defense responsive genes	(Ali et al. 2019)
Stella Maris®	*A. nodosum*	Alkaline	In vivo assay	*Arabidopsis thaliana*	*Pseudomonas syringae, P. aeruginosa, X. campestris*	-	Stimulated plant innate immunity by induction of stress-responsive genes.	(Cook et al. 2018)
Seasol®	*Durvillaea potatorum and A. nodosum*	Alkaline	Root drench	Broccoli	*Plasmodiophora brassicae*	Clubroot	Reduced the number of plasmodia formed in the root hairs	(Wite et al. 2015)
Seasol Commercial®	*D. potatorum, A. nodosum*	Alkaline	Root drench	*A. thaliana*	*Phytophthora cinnamomi*	-	Suppressed pathogen growth by the induction antioxidative defense pathways	(Islam et al. 2020)
*Ascophyllum nodosum*extract (Acadian Seaplants)	*A. nodosum*	Alkaline	Foliar Spray	Carrot	*Alternaria radicina* and *Botrytis cinerea*	Black rot, *Botrytis*blight	Confer immunity against pathogens by eliciting the expression of defense related genes or proteins	(Jayaraj et al. 2008)
*A. nodosum*extract (Acadian Seaplants)	*A. nodosum*	Alkaline	Foliar spray, root drench	*S. lycopersicum*	*Alternaria solani, X. campestris pv vesicatoria*	*Alternaria*blight; Bacterial leaf spot	Protect plants by eliciting JA/ethylene dependent signalling pathways	(Ali et al. 2016)
*A. nodosum*extr	*A. nodosum*	Alkaline and	Root drench	*Arabidopsis*	*P. syringae, Sclerotinia sclerotiorum*	Bacterial speck, Stem rot	Controlled progression of diseases by in inducing the	(Subramanian et al. 2011)

act (Acadian Seaplants)		organic fractions					expression of JA-dependent signalling pathway	
AMPEP (Acadian Seaplants)	*A. nodosum*	Alkaline	-	*K. alvarezii*	*Polysiphonia subtilissima*	Ice-ice, goose bumps	Controlled the epiphyte growth and showed reduce disease symptoms	(Loureiro et al. 2021; Loureiro et al. 2012)
AMPEP	*A. nodosum*	Alkaline	-	*K. alvarezii*	*Neosiphonia* sp.	Ice-ice	Improved the growth and reduce *Neosiphonia*infestation	(Borlongan et al. 2011)
AMPEP	*A. nodosum*	Alkaline	-	*K. alvarezii*	*Neosiphonia apiculata*	Ice-ice	Confer biotic stress tolerance against endophytes	(Ali et al. 2018)
*A. nodosum*extract	*A. nodosum*	Alkaline	Foliar spray	*Fragaria × ananassa*	*Podosphaera aphanis*	Powdery mildew	Reduced incidence and severity of powdery mildew by induction of defense related enzymes	(Bajpai et al. 2019)
Liquid Seaweed Extract (LSE)	*A. nodosum*	Alkaline	Foliar spray	*Triticum aestivum*	*Fusarium graminearum*	*Fusarium*head blight (FHB)	Increased resistance against FHB by inducing expression of defense responsive genes and enzymes	(Gunupuru et al. 2019)
Kelpak®	*Ecklonia maxima*	Aqueous	Root drench	*C. annuum*	*Verticillium dahliae*	*Verticillium*Wilt	Reduced disease	(Rekanović et al. 2010)
Kelpak®-	*Ecklonia maxima*	Aqueous	Foliar spray, soil drench	*S. lycopersicum*	*Meloidogyne incognita*	-	Increased plant growth and lessened infestation	(Crouch and Van Staden 1993)
Kelpak®, OSMO®	*A. nodosum*and	Aqueous, alkaline	Soil drench	*S. lycopersicum*	*Meloidogyne chitwoodi* and *Meloidogyne hapla*.	Root-knot	Reduced hatching, infectivity, and	(Ngala et al. 2016)

	Ecklonia maxima						sensory perception of nematodes	
K-sap	*Kappaphycus alvarezii*	Aqueous sap	Foliar spray	*S. lycopersicum*	*Macrophomina phaseolina*	charcoal rot	Reduced pathogen infestation by differentially regulating the expression of defense-related genes and phytohormone levels	(Agarwal et al. 2016)
Ulva armoricana extract	*U. armoricana*	Aqueous	Foliar spray	*P. vulgaris, Vitis Vinifera, Cucumis sativus*	*Erysiphe polygoni, E. necator, Sphareotheca fuliginea*	Powdery mildew	Protected plants against powdery mildew	(Jaulneau et al. 2011)
Algal powder	*Gracilaria confervoides*	Dry powdered	Soil amendment	*C. sativus*	*Rhizoctonia solani, Fusarium solani, Macrophomina phaseolina*	-	Antifungal activity	(Soliman et al. 2018)
Seaweed extracts	*Ulva lactuca, Caulerpa Sertularioides, Padina gymnospora, Sargassum liebmannii*	Aqueous	Soil drench, foliar spray	*S. lycopersicum*	*Alternaria solani*	Early blight	Reduced necrotic lesion	(Hernández-Herrera et al. 2014)]
Seaweed extracts	*Ulva lactuca, Sargassum filipendula* and *Gelidium serrulatum*	Alkaline	Foliar spray	*S. lycopersicum*	*Alternaria solani and Xanthomonas campestris pv vesicatoria*	Early blight, bacterial spot	Reduced disease severity by inducing the activities of defense enzymes and expression of genes involved defense signalling pathways	(Ramkissoon et al. 2017)

*U. lactuca*extract	*U. Lactuca*	Aqueous	In vitro assay	*Malus domestica*	*Penicillium expansum* and *Botryt is cinerea*	Blue and gray mould	Reduced the lesion by activating antioxidant-related enzyme and phenylpropanoid metabolism	(Briand et al. 2010)
*U. lactuca*extract	*U. Lactuca*	Aqueous, organic fractions	In vitro assay	*Citrus sinesis*	*Penicillium digitatum*	Citrus green mold	Reduced spore germination	(Salim et al. 2020)
Ulva extract	*Ulva* spp.	Aqueous	Foliar spray	*Medicago truncatula*	*Colletotrichum trifolii*	-	Elicited the defense response by inducing the expression of defense-related gene	(Cluzet et al. 2004)
Seaweed extracts	*Cystoseira myriophylloides, Laminaria digitata and Fucus spiralis*	Aqueous	Foliar spray	*Nicotiana benthamiana*	*Pseudomonas syringae* pv. *tabaci*	wildfire	Controlled the progression of wildfire disease by inducing antioxidant defenses	(Esserti et al. 2018)
-	*S. tenerrimum, S. wightii, S. swartzii*	Dry powder	Soil amendment	*Helianthus annuus*	*Macrophomina phaseolina, F. solani,*	Root rot disease	Controlled the progression of disease in plants	(Ara et al. 1996)
S-extract	*S. tenerrimum*	Aqueous	Foliar spray	*S. lycopersicum*	*Macrophomina phaseolina*	Charcoal rot	Stimulated plant defenses by regulating antioxidative and phytohormone metabolism	(Khedia et al. 2020)
*S. vulgare*extracts	*S. vulgare*	Aqueous, organic fractions	In vitro assay	*Solanum tuberosum*	*Pythium aphanidermatum*	*Pythium*leak	Antifungal activity against pathogen	(Ammar et al. 2017)

*S. vulgare*extracts	*S. vulgare*	Aqueous, organic fractions	In vitro assay	*Solanum tuberosum*	*Fusarium oxysporum f. sp. tuberosi*	*Fusarium*Dry Rot	Controlled the progression of disease in tubers	(Ammar et al. 2017)
Seaweed extract	*Sargassum polycystum*	Aqueous	Foliar spray	*Hevea brasiliensis*	*Phytophthora palmivora*	Leaf fall	Foliar spray confers resistance by inducing systemic acquired resistance triggered enzymes and anti-oxidative defense enzymes	(Khompatara et al. 2019)
Sea algal product	*Sargassum fusiforme*	Aqueous	Foliar spray	*S. lycopersicum*	*P. infestans; B. cinerea; Odium sps.*	Late blight, grey mold, powdery mildew	Foliar spray controlled the progression of late blight, grey mold and powdery mildew	(Sbaihat et al. 2015)
-	*S. vulgare, Acanthophora spicifera*	Alkaline	Foliar spray	*S. lycopersicum, Capsicum annum*	*A. solani and X. campestris*	Early blight, bacterial spot	Induced defense by regulation of expression of genes involved in defense-response and phytohormone biosynthesis	(Ali et al. 2021)
-	*Turbinaria conoides*	Aqueous, alcoholic	In vivo assay	-	*Fusarium oxysporum*	Root rot	Possess antifungal activity	(Selvaraju and Vijayakumar 2016)
Seaweed extracts	*Cystoseira myriophylloides, Laminaria digitata,* and *Fucus spiralis*	Aqueous	Foliar spray	*S. lycopersicum*	*Verticillium dahliae, Agrobacterium tumefaciens*	*Verticillium*wilt of tomato, Crown gall	Induced plant defense by increased activity of defense-related enzymes	(Esserti et al. 2017)

Moreover, ongoing research focuses on isolating specific bioactive compounds from various seaweed species and optimizing their extraction methods. This continuous exploration aims to enhance their efficacy in crop protection, paving the way for the development of commercial biostimulants that leverage the beneficial properties of seaweed extracts (Shukla et al., 2021; Battacharyya et al. 2015). Such advancements not only contribute to agricultural sustainability but also support biodiversity and ecosystem health in agricultural landscapes (Various studies) (Shukla et al. 2016; Kim, 2013).

4. Biological Strategy of Phytopathogen:

Plant growth is linked to complex communities of organisms, and their development is primarily influenced by management practices, soil nutrient availability, environmental conditions, and the equilibrium formed among these elements (Baker et al., 2020). In unbalanced ecosystems, pathogens, pests, and invasive plants can diminish agricultural yield or destroy crops. There is significant interest in creating effective and complementary solutions for the integrated management of phytopathogens and pests, including the use of formulations containing microorganisms with biological control properties (Hamed et al., 2023). In Uruguay, various groups have been researching bacteria suitable for use as biological control agents, demonstrating a distinct interest in the application of biocontrol tactics. In this context, Uruguay has undertaken many initiatives to promote sustainable farming practices, including the establishment of a registration process for biopesticides and biofertilizers, as well as the development of the National Plan for Promoting Agroecological Production. (Bajsa and Rivas., 2023).

Also, Kingdom of Saudi Arabia has assumed many initiatives to study the agricultural activities and factors affecting agricultural sustainability to achieve an appropriate socio-economic planning (Asiry et al., 2013). For example, the molecular characterisation and antagonistic effect of twelve different *Trichoderma/Hypocrea* isolates harvested from the rhizosphere of healthy tomato plants in Abha region, Saudi Arabia has been conducted. Results indicated that *Trichoderma harzianum* is effective biological agent against several pathogenic fungi (Mazrou et al., 2020).

The application of bacteriophages and Acibenzolar-S-methyl (ASM) to manage Asiatic citrus canker in Saudi Arabian field conditions showed the bacteriophages +ASM combination can be an effective tool in the integrated management programs of Asiatic citrus canker disease. (Ibrahim et al., 2017).

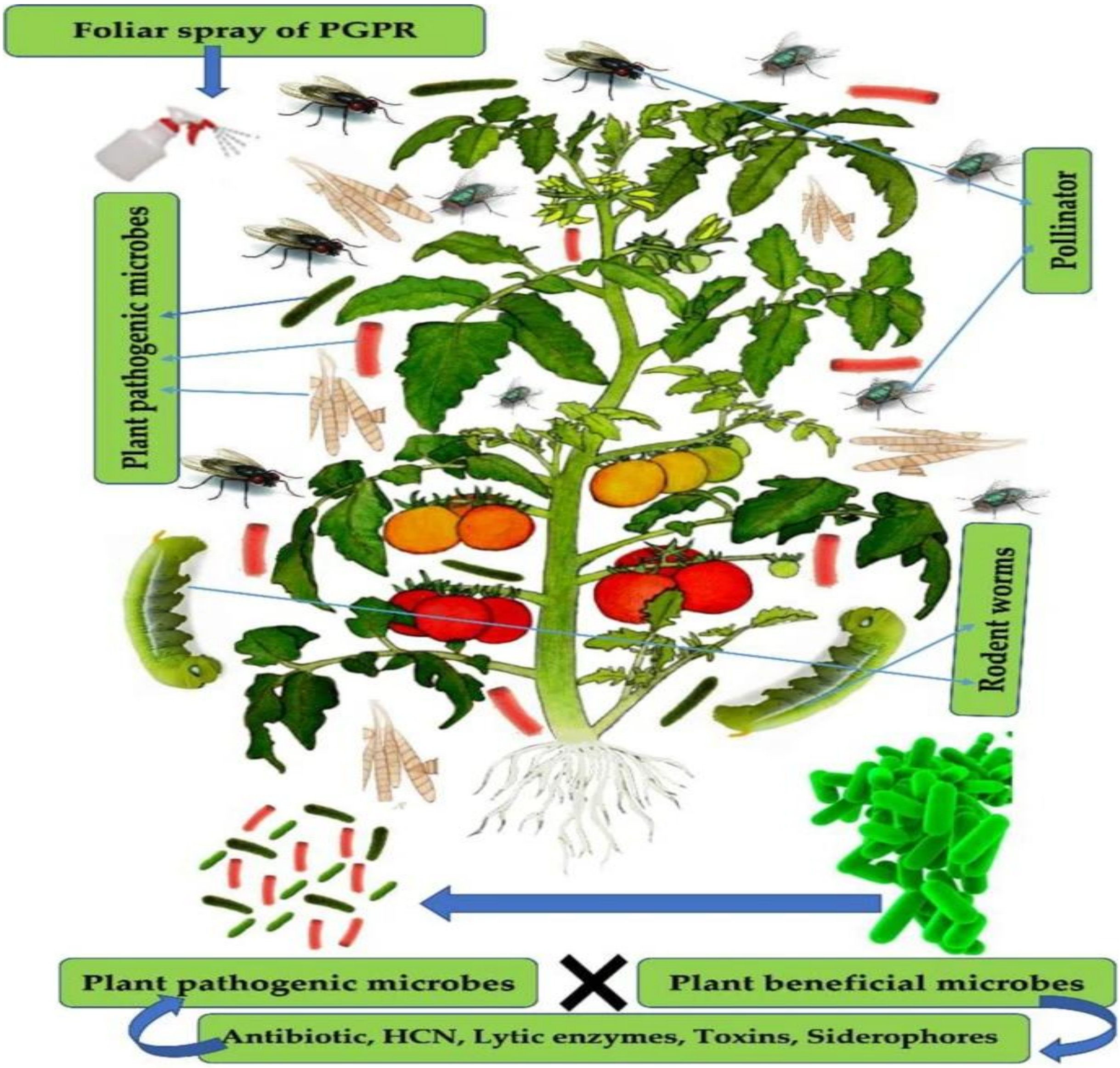


Fig.10. Representative diagram showing the ability of using plant growth promoting microbes to control plant pathogenic pests (Elnahal, et al., 2022).

4.1. Biological Control of Phytopathogen by Cyanobacteria:

Currently, there has been an increase in interest in utilizing bio-alternatives to pesticides to mitigate their adverse environmental effects on ecosystems. The objective of the present review is to highlight the role of cyanobacteria and microalgae as effective biocontrol agent that are environmentally safe and safe for human use as well. Previous studies indicated that, cyanobacteria may serve as an alternative to chemical control (Abdel-Monaim et al., 2016). Where, the efficacy of the cyanobacteria strains exhibited a positive correlation with the levels of Indole Acetic Acid (IAA), total phenolic and flavonoid chemicals, and the protease enzyme as secondary metabolites in the-nitrogen extracts (Ayaz et al., 2023).

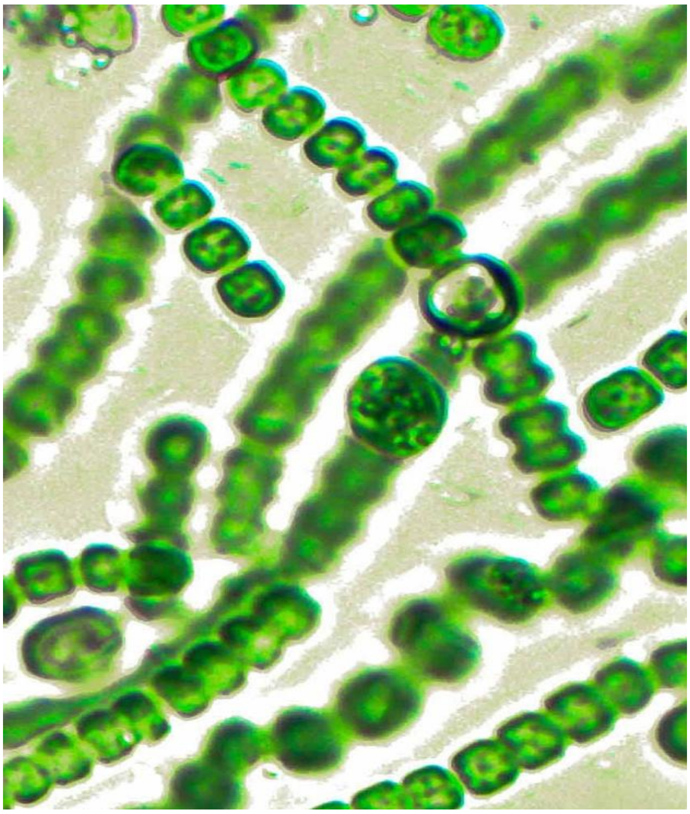


Fig.11. Phenotypic examination of a filamentous cyanobacteria species: A futuristic effective tool in sustainable agriculture (Elagamey et al., 2023).

4.1.1. Cyanobacteria as biocontrol agent of bacterial diseases:

Cyanobacteria have evolved a number of survival strategies to endure in a variety of harsh environments due to their widespread distribution and presence in all conceivable habitats. A considerable number of secondary metabolites that have antimicrobial properties can be produced by cyanobacteria (Yadav et al., 2022).

For instance, the acetone extract of *Oscillatoria agardhii* and *N. muscorum* demonstrated superior efficacy in reducing infection by soil-borne pathogens in both greenhouse and field settings, while also enhancing growth and yield, compared to other cyanobacteria such as *Nostoc muscorum, O. agardhii, S. platensis,* and *A. sphaerica* (Abdel-Monaim et al., 2016; Geries and Elsadany, 2021). The findings of Pimentel et al., (2022), indicate that extracellular components from *N. muscorum* are effective in biocontrol of soybean seedling damping-off.

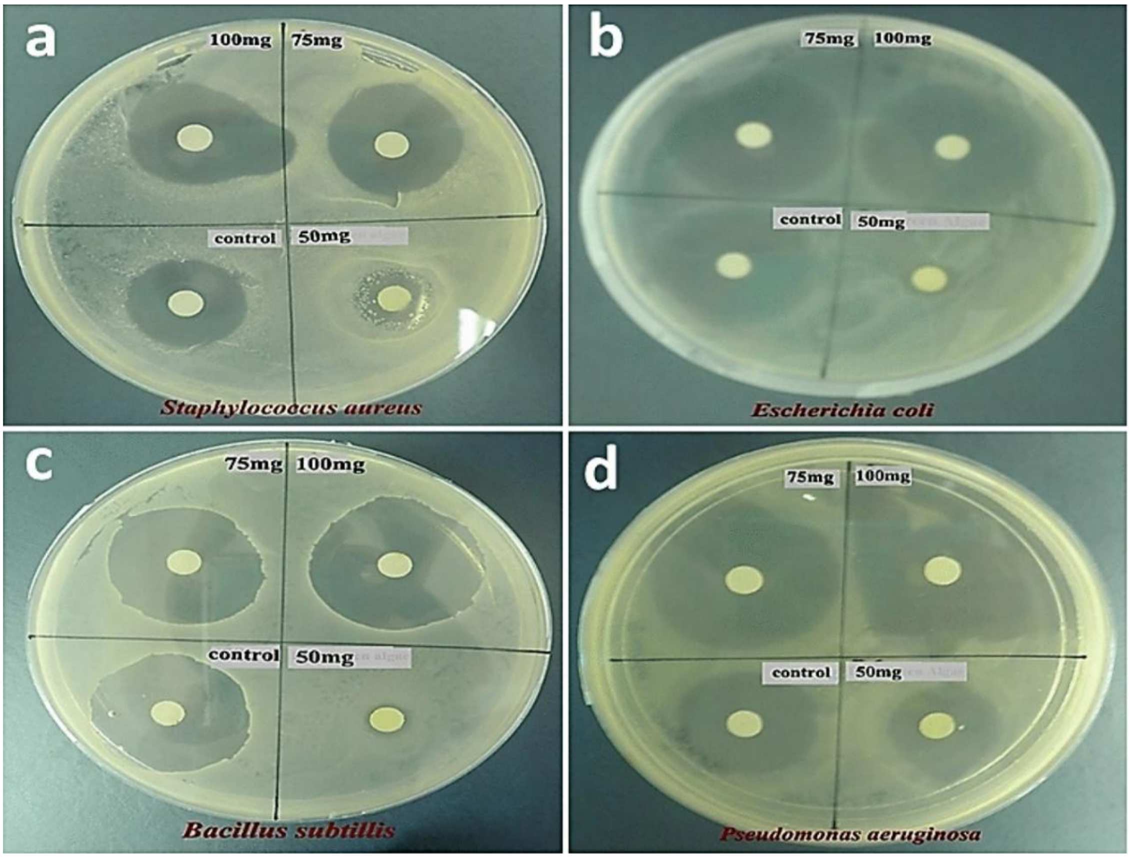


Fig.12. Zone inhibition for (a) *Staphylococcus aureus*(b) *Escherichia coli* (c) *P. aeruginosa* (d) *B. subtilis* using extract of marine cyanobacterium (*Oscillatoria* sp.) isolated from coastal region of west Malaysia (Bhuyar et al., 2020).

4.1.2. Cyanobacteria as biocontrol agent of fungal diseases:

This study examined the impact of foliar application of extracts and cultures of *Botrytis cinerea,* the fungal species responsible for this disease, is a primary contributor to the postharvest decay of commercially available tomatoes. It can also infect plant stems, leaves, and flowers, posing a significant issue in greenhouses. This pathogen is prevalent on crops and weeds, and its spores are readily disseminated by wind. *Botrytis* gray mold typically manifests in the presence of moisture on the plant, which may be from irrigation, fog, dew, or precipitation.

The antifungal activity of water extract and phycobiliproteins of the cyanobacterium, *Anabaena minutissima* strain BEA 0300B against the fungal plant pathogen *Botrytis cinerea* on tomato fruits has been conducted by Righini et al., (2021). The water extract (5 mg/mL) and phycobiliproteins (ranged from 0.3 to 4.8 mg/mL) reduced disease incidence and disease severity on tomato fruits and mycelium growth and colony forming units in vitro. For mycelium growth, a linear phycobiliproteins dose-response was found. Phycobiliproteins preserved cutin and pectin structures by pathogen challenge. In conclusion, *A. minutissima* can be considered a potential tool for future large-scale experiments for plant disease control (Righini et al., 2021).

Also, *Nostoc calcicola and Nostoc linckia* on *Fusarium oxysporum f.* sp. *lycopersici* (FOL), which infects tomato plants (*Solanum lycopersicum*), both in vitro and in vivo. Cyanobacterial isolates were obtained from saline soils in (El-Hamoul and Seidy Salem in Kafr Elsheikh, Egypt) and identified as *N. calcicola* and *N. linckia* (El-Sheekh et al., 2022).

The dry weight, carotene, chlorophyll content, and total phenolic components of the isolates were quantified. *N. calcicola* exhibits superior levels of chlorophyll *a*, carotenoids, and total phenolic compounds in dry weight relative to *N. linckia.* Following 100 days of tomato cultivation, the findings indicated that the application of *N. calcicola* and *N. linckia* resulted in the highest yield of tomato fruits when compared to untreated plants and those infected with *Fusarium*. This suggests that

N. calcicola and N. linckia may function as novel bio-agents for the biological control of the soil fungus *Fusarium oxysporum f. sp. lycopersici* (FOL) (El-Sheekh et al., 2022).

Fig.13. Botrytis gray mold in tomato plant (George., 2020).

4.2. Biological Control of Phytopathogen by Microalgae:

Microalgae synthesize numerous biologically active secondary metabolites, including molecules with antifungal properties (Costa et al., 2019; Asimakis et al., 2022). These may serve as biofungicides. The selection criteria for prospective strains encompass effective antifungal activity against certain phytopathogenic fungi and elevated biomass productivity rates to guarantee adequate biomass generation. Water extracts were produced from 280 strains, including 33 *Cyanophyceae* strains (13 genera), 157 *Chlorophyceae* strains (29 genera), 80 *Trebouxiophyceae* strains

(19 genera), 5 *Klebsormidiophyceae* strains (1 genus), and *1 Zygnematophyceae* strain. These were evaluated against nine phytopathogenic fungi. Forty-five percent of the species exhibited antifungal efficacy against at least one fungal infection (Guiry and Guiry, 2022).

4.2.1. Microalgae as biocontrol agent of bacterial diseases:

Microalgae microbiomes provide both Quorum Quenching (QQ) enzymes and a diverse array of Quorum Sensing (QS) compounds that have demonstrated the ability to disrupt infections (Ghanei-Motlagh et al., 2021). This study screened 19 strains of microalgae and found that a microbial community of *Chlorella saccharophila* and *Chlorella vulgaris,* both degraded N-acyl Homoserine Lactones (AHLs), leading to the inhibition of violacein production in the reporter strain. The *Chlorella saccharophila*-associated microbiome dramatically inhibited bacterial quorum sensing and Acyl Homoserine Lactone (AHL) regulated bioluminescence in the pathogen *Vibrio harveyi* when utilizing an *E. coli* (JB523) strain sensitive to N-(3-oxohexanoyl)-L-homoserine lactone.

Toribio and coworkers, 2021 tested sonicated extracts of cyanobacteria with microalgae of the genera *Leptolyngbya, Nostoc, Chlorella,* and *Scenedesmus* for controlling bacterial canker caused by *Clavibacter michiganensis* subsp. *michiganensis* on tomato plants. The bioassays on tomato seedlings showed that root application of *Scenedesmus*-677 showed a marked inhibitory effect against *C. michiganensis*. while foliar and root application of *Leptolyngbya*-1267 seems to be more related to the strengthening of the plant through the salicylic acid route. These preliminary results could serve as the basis for a deeper characterization of the biopesticidal and biostimulant effect of both strains, as well as to reveal the benefits derived from the combination of both capacities (Toribio et al., 2021).

The antimicrobial activity of the biopesticidal extracts of *Chlorella thermophila* cultivated in nutrient-rich dairy wastewater as a growth medium against

Xanthomonas oryzae and *Pantoea agglomerans*, the causative agent of bacterial rice blight, is assessed through in vitro studies. The biomass extract is able to inhibit the growth of *X. oryzae* and *P. agglomerans*. Mass spectroscopy analysis indicates the presence of Neophytadiene that has previously been reported for the inhibition of several pathogenic bacteria and fungi. Several other value-added products such as linoleic acid and nervonic acids have also been detected in the microalgal biomass which have extremely high nutraceutical and medicinal values (Mohanty et al 2023).

In vitro examination of hexane extracts of *Dunaliella salina,* a green microalgal species demonstrated antibacterial activity against several bacterial plant pathogens. In vivo studies using hexane extracts of *D. salina* against *Pseudomonas syringae* pv. tomato and *Pectobacterium carotovorum* subsp. *carotovorum* on young tomato plants and fruits of tomato and zucchini, respectively. The treated young tomato plants exhibited a reduction of 65.7% incidence and 77.0% severity of bacterial speck spot disease. Similarly, a reduction of soft rot symptoms was observed in treated tomato and zucchini fruits with a disease incidence of 5.3% and 12.6% with respect to 90.6% and 100%, respectively, for the positive control (Ambrico et al., 2020).

4.2.2. Microalgae as biocontrol agent of fungal diseases:

Fungal infections frequently occur in agriculture, resulting in diseases such as leaf blight, vascular wilt, root rot, and damping off (Asimakis et al., 2022). Intensive agricultural operations utilize pesticides in conjunction with synthetic fertilizers for crop protection and production enhancement. Nonetheless, their prolonged overutilization has resulted in environmental issues like soil salinization, eutrophication of aquatic systems, and ocean acidification (Wang et al., 2018; Costa et al., 2019). These compounds are harmful to the rhizosphere microbial community, which is crucial for plant health and disease resistance (Yuan et al., 2017).

A transition is occurring towards more sustainable "green" agricultural methods, including the application of natural biostimulants and biopesticides to enhance plant development and increase resilience to biotic and abiotic challenges (du Jardin, 2015; Costa et al., 2019). The advantages of natural biopesticides compared to synthetic pesticides encompass their superior biodegradability, resulting in reduced residual presence; their specificity, which enhances safety for non-target organisms like beneficial soil microorganisms; their varied mechanisms of action that diminish the likelihood of microbial resistance; and their diminished impact on environmental and human health (Costa et al., 2019; Asimakis et al., 2022).

Several microalgae were tested for their antimicrobial activity against the plant pathogen *Phytophthora cactorum,* a phytopathogen on strawberry leaves. Although most showed antimicrobial properties however, the extract of *Chlorella sorokiniana* showed the strongest growth inhibition showing a potential for biopesticide application on strawberry leaves infected with *P. cactorum*. This study reveals the potential of microalgae as natural biopesticide for organic or more sustainable regular agriculture (Jokel et al., 2023).

In this context, after 90 days of the *Chlorella fusca* CHK0059 treatment, the incidence of *Fusarium* wilt in the *C. fusca*-treated plants had reduced by 9.8% on average compared to the untreated control. The population density of *Fusarium oxysporum* f. sp. fragariae was also reduced by approximately 86.8% in the *C. fusca*-treated plants by comparison to the untreated control at 70 days after treatment. The results indicate that the microalga *C. fusca* is an efficient biological agent for improving strawberry plant growth and suppressing *Fusarium* wilt disease in organic strawberries (Kim et al., 2020).

The in vitro trials on *Chlorella vulgaris* and *Tetradesmus obliquus* showed a similar inhibitory effect against the phytopathogenic fungus *Fusarium oxysporum* to that of the positive control of the chemical fungicide (Rovral, BASF® and Biocontrol T34, Biocontrol Technologies® S.L.). *C. vulgaris* aqueous suspensions at 3.0 g L^{-1} led to a reduction of 63% of fungal growth. While *T. obliquus* at 0.75 g L^{-1} inhibited fungus growth by 64%. Results of in vivo trial on spinach using the same controls revealed a lower severity and disease incidence and a reduction in the disease area under the disease progress curve when spinach was treated with the microalgae suspensions. Overall, these findings highlight the potential of *C. vulgaris* and *T. obliquus* suspensions as promising biocontrol agents against *F. oxysporum* in spinach when applied through irrigation (Viana et al., 2024).

Chlorella sp. extract was evaluated for their biostimulant effects and fungicide activity against the soil-borne pathogen *Rhizoctonia solani* on tomato. *Chlorella* sp. extract increased seedling dry weight at all concentrations, particularly at 2.5 mg/mL (19.2%). Furthermore, root rot disease caused by *R. solani* was reduced by *Chlorella* sp. extract at all tested concentrations (Righini et al., 2020).

The antifungal effect of *Chlorella vulgaris* extract against potato pathogen, *Rhizoctonia solani* was evaluated in vitro and in the greenhouse. Methanolic extract of *C. vulgaris* had significant effects on the growth of the pathogenic fungi, either by inhibiting fungal mycelia growth in solid and liquid media or the formation of infection cushion, that was observed by light microscope. The inhibitory effect on fungal growth was a dose dependent. The application of *C. vulgaris* extract significantly reduced disease severity and improved the quality and quantity of potato tubers yield. The chemical composition of the methanolic crude extract of *C. vulgaris* was analyzed by GC-MS. Palmitic and oleic acids, glycine and phenol were among the major compounds found in the methanolic crude extract which exhibited variable efficiency against the pathogen in vitro (Al-Nazwani et al., 2021).

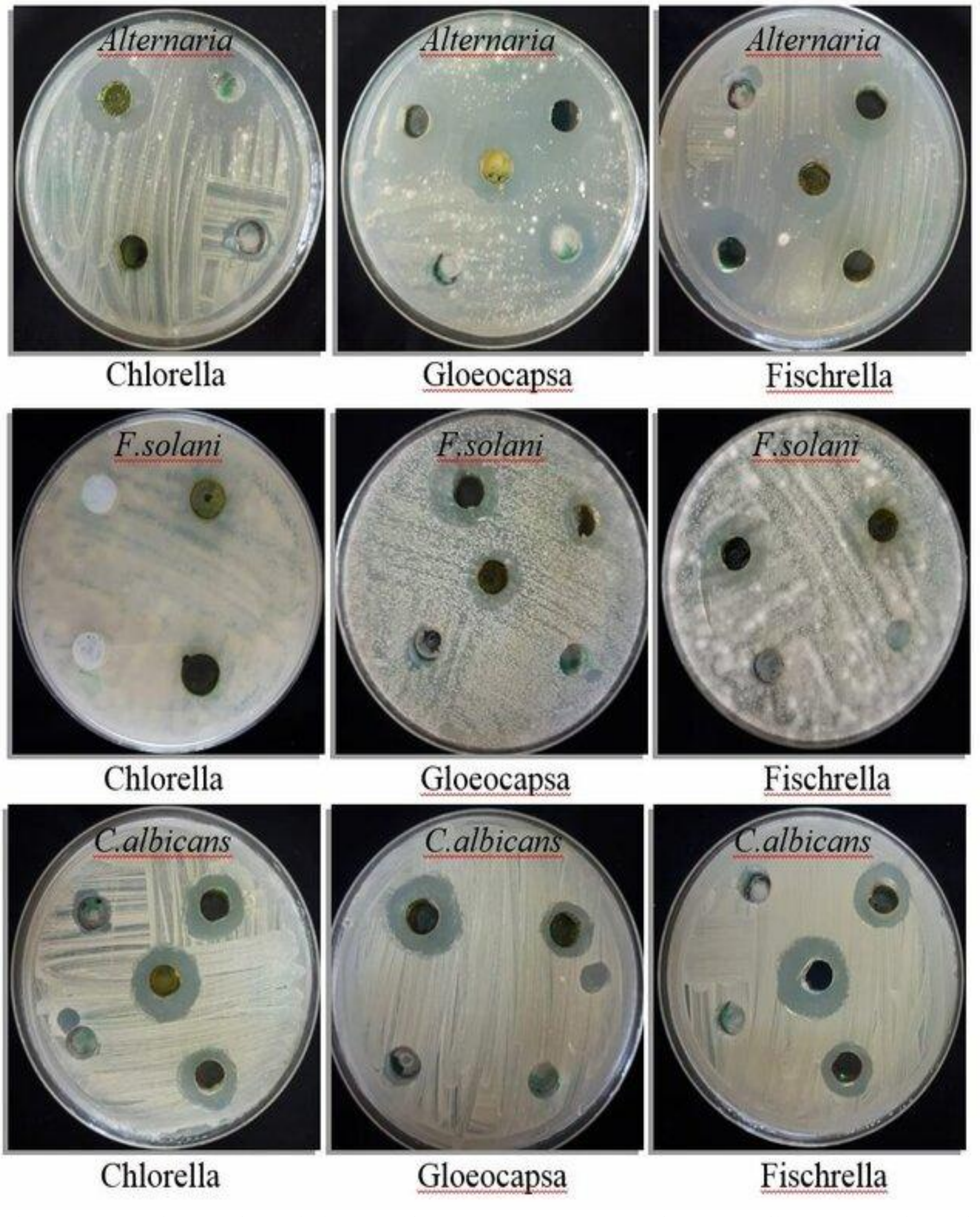


Fig. 14. Antifungal activity of b-carotene extracted from different microalgae species (Al-Taie et al., 2020).

4.3. Biological control of phytopathogen by seaweeds:

The marine macroalgae (seaweeds) are including many phyla; red microalgae (*Rhodophyta*), green microalgae (*Chlorophyta*), and brown microalgae (*Phaeophyta*). Algal composition is influenced by harvest season, chemicals such as polysaccharides, geographic location (Schiener et al. 2015), important elements (Cu, Zn, Mn, Co, Mo, etc.). Moreover, seaweeds exhibit antiviral, antioxidant, antibacterial, and antifungal properties, which have numerous uses in cosmetics, bioactive compounds, medicines, and pigment production (Sharma and Sharma 2017). Consequently, algal application significantly contributes to soil fertility and agricultural yield across many agronomic and horticultural crops (Arioli et al. 2015). The enhancement of postharvest longevity, disease management, and resilience to biotic and abiotic stimuli in fruits has been documented following the application of several algae extracts (Esserti et al. 2017). Seaweeds, as photosynthetic organisms, convert sunlight into chemical energy, which is subsequently stored in carbs. Under typical conditions, photosynthesis prevails, enabling seaweeds to accumulate their carbohydrate content.

4.3.1. Seaweeds as biocontrol agent of bacterial diseases:

Active metabolites, including alkaloids, sterols, peptides, and phlorotannins, generated by marine macroalgae exhibit extensive biocontrol activities against various ecosystem pathogens (Abdel-Raouf et al. 2015). These metabolites have garnered significant attention due to their antibacterial, antioxidant, and cytotoxic properties (Moubayed et al. 2017). For instance, the leaf spot disease of *Gymnema sylvestre,* induced by *Pseudomonas syringae,* can be mitigated by a methanolic extract derived from *Sargassum wightii*, although the ethyl acetate extract demonstrates minimal efficacy (Shah, et al., 2021). Numerous additional studies indicate that various taxa such as *Turbinaria conoides*, *Ulva lactuca*, *G. verrucosa*, *Chaetomorpha antennina*, and *Halimeda tuna* exhibit antibacterial efficacy against

P. syringae, although a notable effect was observed from the acetonic extract of *Sargassum polyceratium* (a brown macroalga) against *Erwinia carotovora, Escherichia coli* (Shah, et al., 2021). Esserti et al., (2017) documented a decrease in crown gall disease in tomatoes induced by *Agrobacterium tumefaciens* with the foliar application of an aqueous macroalgal solution derived from *Fucus spiralis* and *Cystoseira myriophylloides.*

4.3.2. Seaweeds as biocontrol agent of fungal diseases:

As previously stated, seaweeds are rich source of bioactive and nutraceutical compounds such as Ulvans, Alginates, Fucans, Laminarin, and Carrageenans, can elicit defence responses in plants, thereby augmenting protection against pathogens. Numerous studies have demonstrated the significant role of infection resistance conferred by algal extracts exhibiting antifungal properties. The mycelial growth of *Aspergillus* spp., *Penicillium* spp., and *Fusarium oxysporum* was markedly inhibited by *cyclohexanic* and aqueous extracts from *Sargassum* sp. (Khallil et al. 2015). The cyclohexane and aqueous extracts from *Sargassum* sp, a brown alga reduce the mycelial growth of *Aspergillus* spp. by 37–54.5%.

Padina gymnospora and *Sargassum laftifolium,* which contain methanolic extract, suppressed colonies of *Rhizoctonia* and *Fusarium solani* (Ibraheem et al. 2017). Extracts of *Ascophyllum nodosum, Stypopodium zonale, Fucus spiralis, Pelvetia canaliculata,* and *Sargassum muticum* contain terpenes and phenols that inhibit the growth of *Colletotrichum lagenarium* (De Corato et al. 2017) indicated that the mycelial growth and spore germination of *Botrytis cinerea* were entirely suppressed by *Undaria pinnatifida* and *Laminaria digitata.* Moreover, the methanolic extract of *Gracilaria edulis* markedly inhibits the mycelial growth of *Macrophomina phaseolina* (Ambika and Sujatha., 2015), while the aqueous extract derived from *Gracilaria edulis* reduces infections of *Corallina sp*. and *Halopithys* in zucchini (Roberti et al., 2016).

5. Types of Bioactive Compounds Produced by Cyanobacteria and Algae

5.1. Exopolysaccharides

Cyanobacteria and algae during their growth produce bioactive polymers made of sugar residues with a high molecular weight known as exopolysaccharides (EPSs). These molecules are essential for the microbes' survival and adaptation and have great promise in the fields of industry, agriculture, ecology, and medicine (Mota et al., 2022; Mouro et al., 2024).

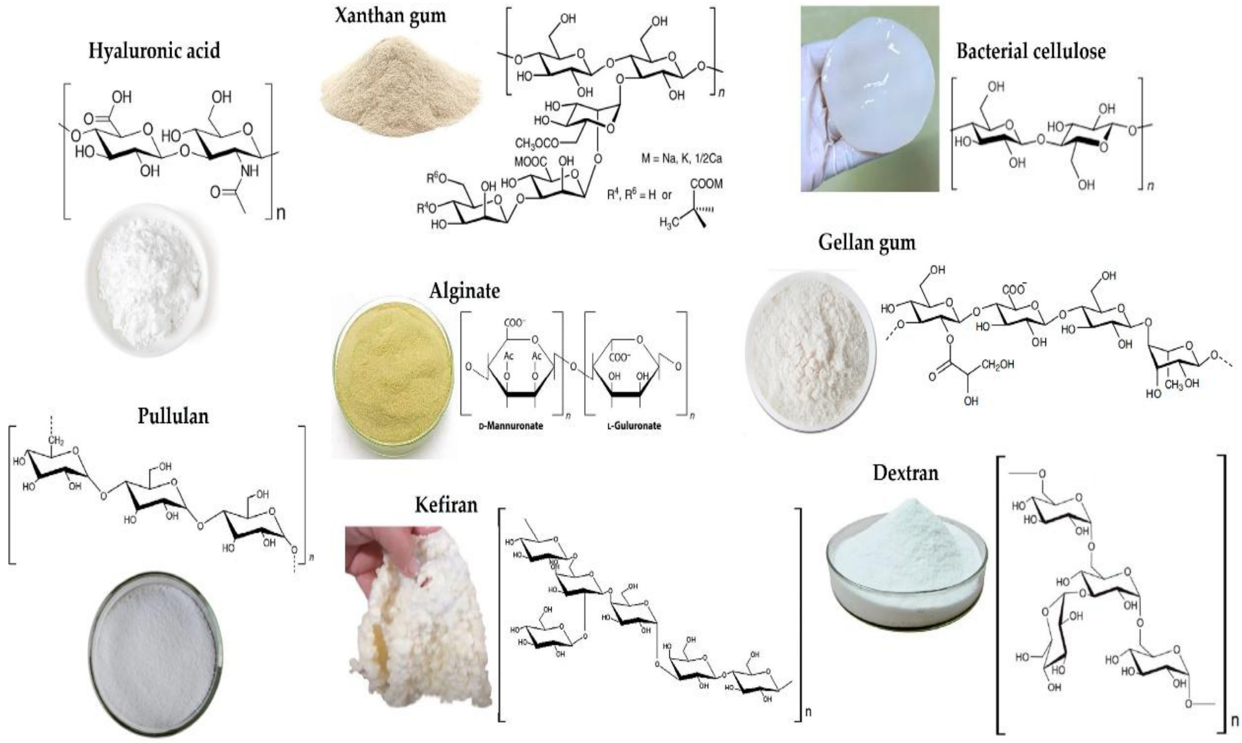


Fig. 15. Chemical structures of the different kinds of exopolysaccharides (EPSs) produced by algae and cyanobacteria (Guerrero et al., 2024).

To help cyanobacteria and algae to survive in harsh environments, EPS creates a protective matrix around them in nature. This matrix protects cells from drying out, harmful chemicals, and ultraviolet light while also providing structural support and aiding in moisture retention. Atmakuri et al. (2024) found that EPS helps microbes to adhere to surfaces, which in turn forms biofilms. These biofilms may help in keeping aquatic ecosystems stable.

EPSs have many different bioactive features, such as anti-inflammatory, antioxidant, antiviral, and antibacterial activities. Wound healing, drug delivery systems, and pharmaceutical bioactive agents are just a few of the biomedical uses of EPSs due to its desirable properties (Kumari et al., 2023). For example, researchers are investigating EPSs biocompatibility and hydrogel-forming capabilities for using them in tissue engineering and controlled-release medication or cell encapsulation (Abdel-Wahab et al., 2022).

Cyanobacteria- and algae-derived EPSs have recently gained interest for their potential use as emulsifiers, thickeners, and stabilizers in a variety of industrial applications, including those involving food and personal care. Because of their non-toxicity and biodegradability, they are frequently chosen over synthetic polymers. By binding and immobilizing contaminants and heavy metals, some EPS also demonstrate promise in bioremediation and wastewater treatment (Laroche, 2024). EPSs have gained great concern in the scientific community due to their multiple applications. Therefore, researchers are always trying to better understand their structure-function correlations and find ways to produce them (Mouro et al., 2024). Cyanobacteria such *N. muscorum* improve the soil stability of saline soil by excreting exopolysaccharides (Caire et al. 1997). Therefore, using alga and cyanobacteria as biofertilizers in uncultivated soil such as calcareous and sand and saline soil could be a good choice for reclaiming soil for agricultural use (Hedge et al. 1999).

5.2. Phenolic compounds

Algae and cyanobacteria are known to produce variable kinds of phenolic compounds. These molecules play an important role in their survival and have great promise for use in agriculture, food production, and industry. The presence of aromatic rings connected to these molecules with one or more hydroxyl groups is what gives them their potent antioxidant and bioactive characteristics (Del Mondo et al., 2021).

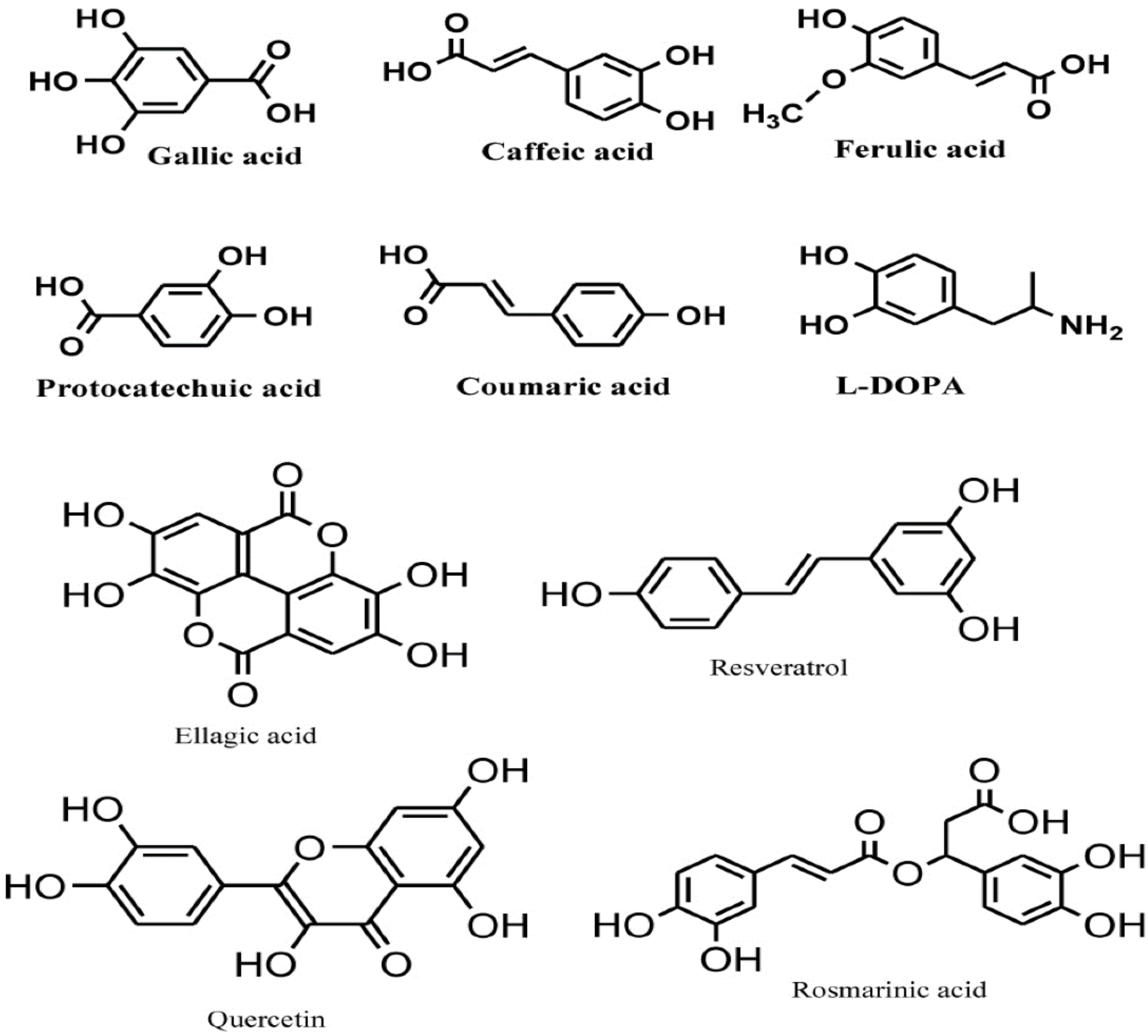


Fig. 16. Common phenolic compounds found in algae comprise an aromatic ring, bear one or more hydroxyl substituents and range from simple phenolic molecules to highly polymerized compounds (modified from Velderrain-Rodríguez et al., 2014).

Phenolic compounds play role in shielding cells from harmful environmental factors as UV radiation, oxidative stress, and pathogenic assaults in cyanobacteria and algae (Cichoński, and hrzanowski, 2022). For example, substances such as tannins, flavonoids, and phenolic acids serve as antioxidants and sunscreens naturally, counteracting the negative effects of reactive oxygen species (ROS) that are produced when stress is present (Michalak, 2022). This defense mechanism not only helps the creatures survive in harsh conditions, but it also shows how useful they may be in medicine and the beauty industry (Hajam et al., 2023).

Polyphenolic compounds are produced as secondary metabolites during algae and cyanobacteria growth. These biochemicals are a vast and varied class of chemical compounds with an aromatic hydrocarbon group immediately linked to a hydroxyl group (-OH) (Jimenez-Lopez et al., 2021). Substructures with one phenolic hydroxyl group are called "phenols." Benzenediols are a kind of catechol and resorcinol, have two hydroxyl groups. Benzene triols are types of pyrogallol and phloroglucinol, which have three hydroxyl groups. Tannins are phenolic compounds found in many terrestrial algae, cyanobacteria and higher plant. Their strong antioxidant activity has made them a popular topic of study in recent decades (Ravichandran et al., 2024).

Phenolic acids consist of aromatic rings linked to the carboxyl and hydroxyl groups. Among the major subsets of phenolic acids, hydroxybenzoic acid, phenylacetic acid, hydrocinnamic acid, and phenylpropionic acid which originate in the shikimate pathway (Al Mamari, 2021). According to previous reports, the antioxidant defense mechanisms in photosynthetic organisms rely on phenolic acids which contribute to alleviating stress induced by hydroxyl radicals (OH) and reactive oxygen species (ROS) (Hajam et al.2023). Phlorotannin produced by *Ecklonia cava* has anti-UVB properties and lessens the photodamage caused by UVB rays (Shim et al., 2009).

5.3. Fatty acids

Many species of cyanobacteria and algae produce cyclic lipopeptides that have long chains of fatty acids (Dembitsky, 2022). Macrolactone and macrolactam rings are usually formed by cyclic lipopeptides that contain fatty acids with β-hydroxy or β-amino residues. The frequently powerful antagonistic effects of these chemicals have garnered a lot of interest. According to Fewer et al. (2021), cyanobacteria and algae produce fatty acids which play a role in their biology and may have variable applications in bioenergy, food, healthcare…. etc.

Fatty acids give structural support and flexibility to the cell membranes of cyanobacteria and algae. The ability of cells to respond to changes in environmental factors, such as temperature and salinity mainly depends on them (Ali and Szabó 2023). In addition, these microbes may thrive in conditions with low nutrients because fatty acids are building blocks for compounds that store energy such as triglycerides and wax esters (Alvarez et al., 2021).

Fatty acids derived from algae and cyanobacteria have bioactive characteristics that make them useful for more than just fundamental cellular processes. For example, omega-3 fatty acids which are abundant in microalgae and are known to have positive effects on the heart and nervous system (Tyagi et al., 2024). The immunomodulatory and anti-inflammatory properties of these chemicals make them useful in the treatment and prevention of long-term health problems such diabetes, cardiovascular disease, and neurological illnesses (Elbandy, 2022).

Fatty acids extracted from algae and cyanobacteria are much requested for their health advantages, but they also hold enormous promise as environmentally friendly biofuels. It is possible to produce biodiesel from the large quantities of lipids, such as fatty acids, that many species can store. These microbes are considered as potential solutions to energy problems and alternatives to fossil fuels (Maltsev and Maltseva, 2021). According to Ahmed et al. (2024), more research and development should focus on utilizing these molecules as sustainable solutions because of their ecological relevance and promise in health, nutrition, and energy. The first identified microalgal fatty acid known as Chlorellin which was isolated from *Chlorella* sp. This fatty acid inhibited the development of both gram-positive and gram-negative bacteria (Pratt et al., 1944).

5.4. Antibiotic

Antibiotics are normally produced by a number of marine and freshwater algae and cyanobacteria that can suppress the growth of many epibionts, including bacteria, viruses, fungus, and others. The antibiotic properties seem to be dependent on several variables, including the kind of algal species, the kind of microbes, the time of year, and the growing circumstances (Gan et al., 2024).

The antimicrobial properties of some marine algae are attributed to several extractable chemicals, including halogenated compounds and cyclic polysulfides (Toma and Aziz, 2023). The bioactive antibiotics produced by algae and cyanobacteria are very important in biotechnology and ecology. In order to compete with other microbes in their habitats, such bacteria and fungus, these microbes naturally create antibiotics as secondary metabolites (Żymańczyk-Duda et al., 2022). Because of their unusual structures and action processes, the antibiotic compounds they generate are promising new therapeutic targets (Stirk and van Staden, 2022).

Nostocyclopeptides, Scytonemin, and Microcystin derivatives are only a few of the many antibiotics that are produced by cyanobacteria. These substances frequently have strong antimicrobial, antifungal, and antiviral properties (Saeed et al., 2022). For example, *S cytonemin* had dual use as an antibacterial and a natural UV protector. Nostocyclopeptides have been investigated for their capacity to prevent bacterial growth. Because of their qualities, they may find use in the fields of agriculture, industry and medicine (Nawaz et al., 2023).

Microalgae and other types of algal species are involved in the generation of antibiotics and other substances with bioactive and antibacterial properties. Examples of substances that have shown promise in combating infections, particularly bacteria resistant to antibiotics, include halogenated metabolites and fatty acid derivatives derived from algae. Antimicrobial resistance is a major problem all around the world, and these algae antibiotics are useful because of their broad-spectrum action (Stirk and Staden, 2022).

Production of antibiotics and other bioactive chemicals from microalgae and cyanobacteria has been a hot topic in the past 10 years. Microalgae extracts have been found to yield a surplus of antibiotic compounds, some of which have quite unique structures (Saeed et al., 2022).

According to Bouyahya et al. (2024), microalgae extracts include several bioactive chemicals that might be used in agriculture, human or veterinary medicine, or both. Since microalgae can be cultured to create bioactive molecules, they are an appealing natural supply of these chemicals. Because of this, structurally complicated compounds that would be very challenging, if not impossible, to synthesize by chemical means may be manufactured by microalgae (Chen et al., 2022).

5.5. Enzymes

As a result of their bioactive properties and the important roles they play in their metabolism, enzymes produced by algae and cyanobacteria have great promise for use in a wide range of commercial, ecological, and therapeutic contexts (Saeed et al., 2022). Their ability to catalyze metabolic processes is what allows these organisms to survive in such a wide variety of harsh conditions, including photosynthesis, nutritional absorption, and stress response systems are all interdependent on them (Mishra, 2024).

Enzymes like RuBisCO and carbonic anhydrase play a critical role in photosynthesis, a process by which cyanobacteria and algae convert carbon dioxide into organic compounds essential for growth and energy storage (Ray et al., 2022). Nitrogenase and nitrate reductase are enzymes that help these organisms to use inorganic nitrogen sources found in their environment. In addition to being essential for the survival of algae and cyanobacteria, these metabolic enzymes show how to improve carbon sequestration and implement sustainable farming methods (Paśmionka et al., 2021). Red seaweed extracts from *Laurencia obtusa* contain a variety of physiologically active substances that could have antibacterial, antioxidant, antiviral, anti-inflammatory, and anticancer properties.

According to Jagtap et al. (2022), there is evidence that algal extracellular enzyme activity is attributed to exo-enzymes, such as chitinases, glucosidases, proteases, and alkaline phosphatases. These enzymes might impact the development of microorganisms, chemical signaling, and biogeochemical cycling within ecosystems. The cyanobacteria *Oscillatoria* sp. and *Scytonema* sp. secrete an extracellular phycoerythrine-like protein, as demonstrated by Karseno et al. (2023). According to Prasanna et al. (2013), *Anabaena laxa* produces hydrolytic enzymes that prevent tomato wilt induced by *Fusarium* species.

There is a great possibility of finding new metabolites and making existing ones more cost-effective by investigating microalgae, which have so far been under-explored. Microscopic algae in its broader definition. New plant protection and pest control preparations can be made possible by the high technical level of controlled culture of microalgae (Brisson et al., 2021).

5.6. Pigments

Pigments are bioactive compounds produced by cyanobacteria and algae. These compounds are essential for many biological processes and have many practical uses. Photosynthesis relies on these naturally occurring pigments, which allow these to efficiently absorb light energy. These pigments include chlorophylls (*a* and *b*), carotenoids, phycobiliproteins, and many more. The antioxidant activity, anti-inflammatory, antibacterial, and anticancer actions displayed by these pigments extend beyond their function in energy generation (Patel et al., 2022).

Pigments shield cyanobacteria and algae from damaging ultraviolet (UV) radiation and oxidative stress, allowing them to thrive in a wide range of habitats. According to Assunção et al. (2022), the photoprotective substances such as carotenoids and phycobiliproteins mitigate harm induced by excessive light or environmental stress. Because of their bioactive characteristics, pigments are useful for more than just the organisms themselves; they may find use in fields as diverse as biotechnology, medicine, cosmetics, and even food.

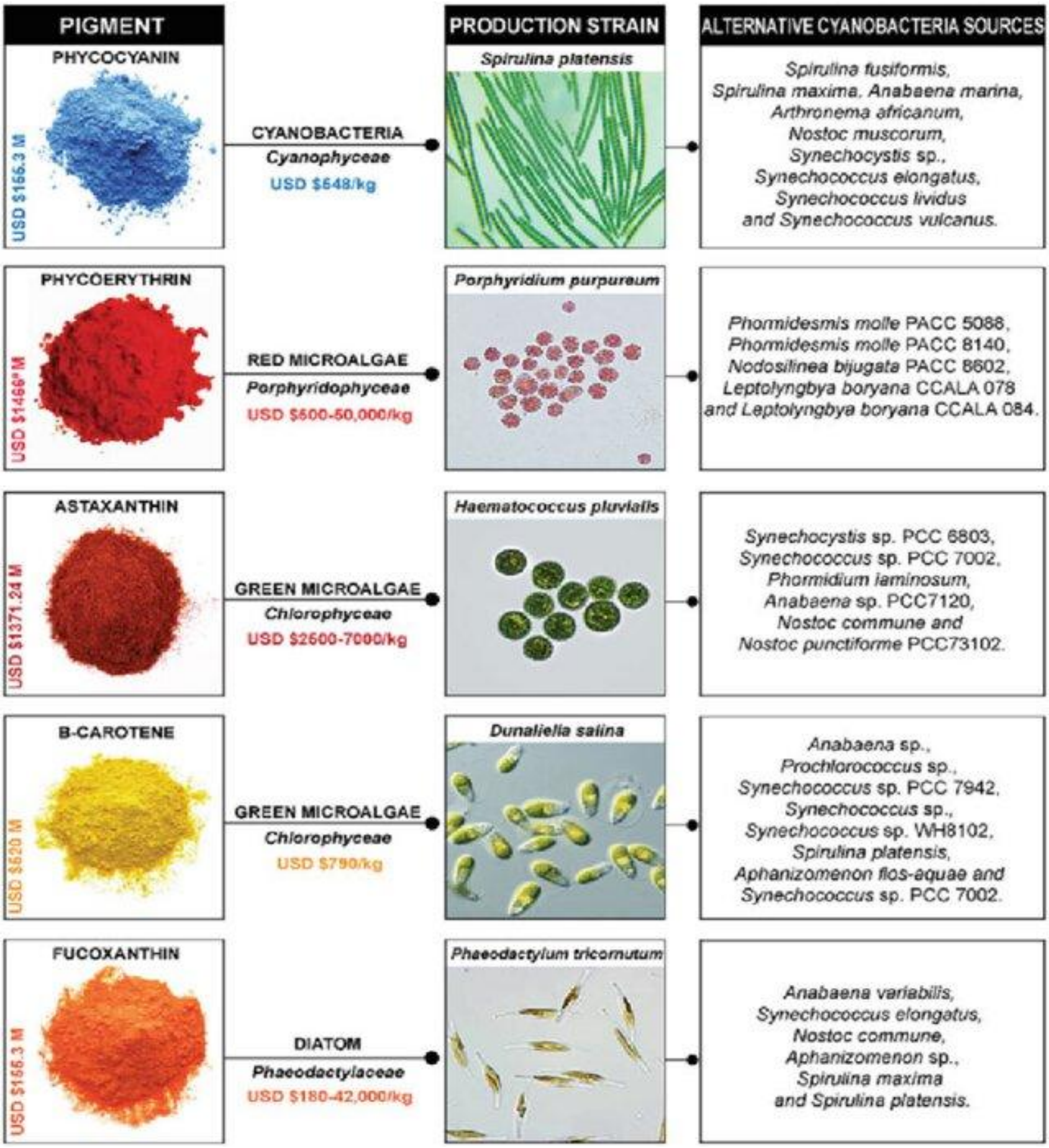
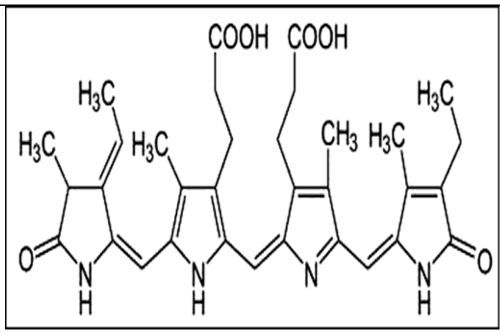


Fig. 17. Commercially available algae and cyanobacterial pigments and their high-pigment strains. The pigments (left), the commercial strain (source, middle) and potential cyanobacterial strains with high pigment content. The micrographs of the commercial strains were obtained from the 'Microalgae Strain Catalogue' (Deepika et al., 2022)

Studies on these pigments have shown that they could be a safe and effective replacement for synthetic chemicals. The health benefits of some pigments, such as phycocyanin and astaxanthin, which include boosting the immune system and protecting cells from chronic illnesses, have attracted a lot of attention in recent years. Algae and cyanobacteria create pigments, which are important bioactive substances with significant ecological and biotechnological value (Aman et al., 2022). According to Chaïb et al. (2021), this pigment, which belongs to the phycobiliprotein family, can hinder the growth of *Chlorella fusca* and *Chlamydomonas* sp., two types of green algae. This suggests that it may have promise as an algicide. Podosphaera xanthii-induced powdery mildew on zucchini cotyledons is controlled by the algae *Spirulina platensis* (Roberti et al. 2016).

Phycocyanin



Astaxanthin

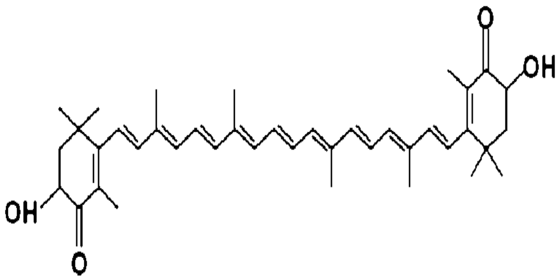


Fig18. Chemical structure of phycocyanin produced by *Spirulina* sp.(Wu et al., 2016) and Chemical structure of Astaxanthin produced by <u>*Hematococcus pluvialis*</u> (Debnath et al., 2024)

5.7. Proteins, peptides, and amino acids

Proteins, peptides, and amino acids are bioactive substances produced by cyanobacteria and algae and are crucial to their physiology and have great promise for use in biotechnology and medicine (Hassan et al., 2022). Photosynthesis, nutrition, and enzymatic activity are just a few of the many cellular functions supported by the essential proteins found in these microbes. A few of these proteins have developed unique characteristics that make them useful in the medicinal, agricultural and industrial field (Qiao et al., 2024).

Peptides aid organisms in developing competition with ambient microbes (Al-Nedawe and Yusof, 2023). Microcystins and cyanopeptolins are powerful peptides produced by cyanobacteria which have specialized biological functions. Kordahi et al., (2024) noted that although microcystins and other similar compounds are hazardous and should be handled with extreme caution, other molecules show potential as pharmacological agents because of their specificity and effectiveness.

According to Srivastava et al. (2022), bioactive substances with different uses in healthcare, agriculture, and environmental management may be found in abundance in proteins, peptides, and amino acids derived from cyanobacteria and algae. Because of their versatility, these microbes have great promise as biotechnological solutions to pressing global issues including the treatment of diseases and the creation of sustainable resources.

5.8. Sterols

All eukaryotic organisms biosynthesize sterols, which are tetracyclic triterpenoids (Desmond and Gribaldo 2009; Volkman., 2016). Sterols are type of lipids are widely present in both macro and microalgae. Notable biological characteristics of sterols and their derivatives include antioxidant and anti-inflammatory effects. Brown algae are high in fucosterol, ergosterol, and chondrillasterol, but red algae are mainly composed of cholesterol (Lordan et al., 2011; Bouzidi et al., 2019; Pradhan et al., 2020). These substances mediate signalling pathways that improve plants' ability to withstand stress and are necessary for the creation of cellular membranes. According to recent research, the strong anti-inflammatory and antioxidant properties of brown algal is attributed to sterols, - particularily fucosterol which -make them suitable for biotechnological uses in plant protection (Hannan et al., 2020; Pradhan et al., 2020). Fucosterol derived from brown algae, for example, has been found to improve wheat's resistance to salinity stress (Pradhan et al., 2021). According to Hannan et al. (2020), ergosterol has also been used to increase immunity against fungal diseases like *Botrytis cinerea* in tomatoes.

5.9. Other bioactive compounds

In addition to sterols, cyanobacteria and algae generate a wide range a wide variety of bioactive chemicals produced which are well acknowledged for their function in controlling plant diseases (Bharathi., 2021). These substances, which include fatty acids, polyphenols, and sulfated polysaccharides, have strong antibacterial properties against a variety of phytopathogens. Sulfated polysaccharides that are isolated from macroalgae, for example, have shown potent inhibitory effects on fungi like *Phytophthora infestans* and *Fusarium oxysporum* (Righini and Roberti, 2019). It has been demonstrated that sulfated polysaccharides derived from the algae *Ulva lactuca* can significantly slow the spread of *Fusarium* wilt in legumes by more than 50% (Righini and Roberti, 2019). Moreover, it has been demonstrated that cyclic peptides and phenazines generated from cyanobacteria inhibit bacterial and fungal pathogens by interfering with their cell walls and metabolic functions (Pandit et al., 2022). Apart from their direct antibacterial properties, these bioactive substances have the ability to strengthen plants' innate immune response by causing systemic resistance. For instance, it has been discovered that applying cyanobacterial extracts activates plant defence genes linked to immunity activated by pathogen-associated molecular patterns (PAMP) (Jose et al., 2024). These compounds are very promising for the development of sustainable biocontrol techniques because of their dual activity, which includes both resistance induction and antibacterial action.

The potential of volatile organic compounds (VOCs) generated by microalgae in biocontrol has also been emphasized by recent studies. It has been demonstrated that VOCs generated by algae, such as hexanal and dimethyl sulfide, limit the formation of bacterial biofilms and reduce spore germination in fungal pathogens (Ryu et al., 2003). Additionally, exopolysaccharides produced by cyanobacteria and algae serve as barriers to prevent pathogen invasion of plant roots in addition to enhancing soil structure (El-Sheekh and Dobara, 2022).

Table 5: Bioactive compounds produced by algae and cyanobacteria

Compound	Source	Properties	Agricultural benefits	References
Polyunsaturated fatty acids (PUFAs)	Microalgae (*Chlorella vulgaris*)	Antimicrobial	Enhances plant health by combating pathogens	Kumaran et al., 2020
Sulfated polysaccharides	Brown Algae	Antifungal	Inhibits *Fusarium oxysporum* growth	Gupta et al., 2013
Phycobiliproteins (e.g, phycocyanin)	Cyanobacteria	Antioxidant	Improved plant growth and stress tolerance	Patel et al., 2006
Polyphenols	Algae	Antioxidants	Protects plants from oxidative stress and enhances resistance to diseases	El-Chaghaby et al., 2019

6. Mechanism of interaction between pathogenic microbes and plant diseases biocontrol agent

Different mechanisms of action are used by the microorganisms in plant pathogen biocontrol (Nega, 2014; Alizadeh et al., 2020; Mbachu et al., 2022). Several authors classified these mechanisms of action into three categories; mixed path antagonism, indirect antagonism, and direct antagonism (Mbachu et al., 2022). Under various experimental conditions, a variety of interactions between organisms lead to biological control; numerous methods are used in the mechanism's characterization. Pathogens have an antagonistic effect on other organisms' presence and activities under nearly all circumstances. Thus, this study has concentrated on the adaptation of several antagonistic mechanisms generated by the directional spectrum linked to the specificity of interactions and the interspecies contact quantity (Fig. 19) (Mohamed et al., 2021).

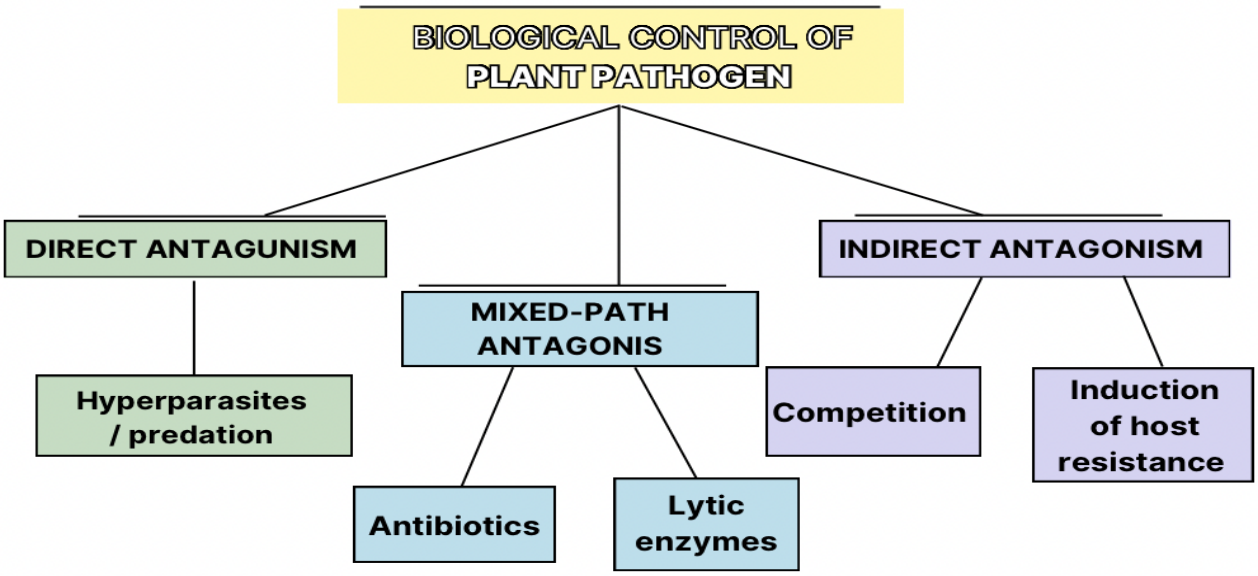


Fig.19. Mechanism of interaction between pathogenic microbes and plant biocontrol agent

Table 6: Types of interspecies antagonisms leading to biological control of plant pathogens (Tripathi et al., 2023)

Type	**Mechanism**	**Example**
Direct Antagonists	Hyper parasitism /predation	Lytic/some nonlytic mycoviruses *Ampelomyces quisqualis Lysobacter enzymogenes Pasteuria penetrans Trichoderma virens*
Mixed-path antagonism	Antibiotics	diacetylphloroglucinol Phenazines -2,4 Cyclic lipopeptide
	Lytic enzymes	Chitinases Glucanases Proteases
Indirect antagonism	Competition	Exudates/ leachates consumption Siderophore scavenging
	Induction of host resistance	Contact with fungal cell walls Detection of pathogen-associated, molecular patterns Phytohormone-mediated induction

6.1. Hyperparasites and Predation:

Hyperparasitism known as the ability of microorganisms (biocontrol agent) to parasitize on other microorganisms (pathogens), using them as a source of food and energy (Mbachu et al., 2022). In hyperparasitism, the pathogen or its spores are directly killed by biological control agents (BCA). In general, there are four main groups of hyperparasites: facultative predators, obligate bacterial pathogens, hypoviruses, and parasites (Mohamed et al., 2021). One obligatory bacterial species known as *Pasteuria penetrans* is employed to control root-knot nematodes which attack numerous plants.

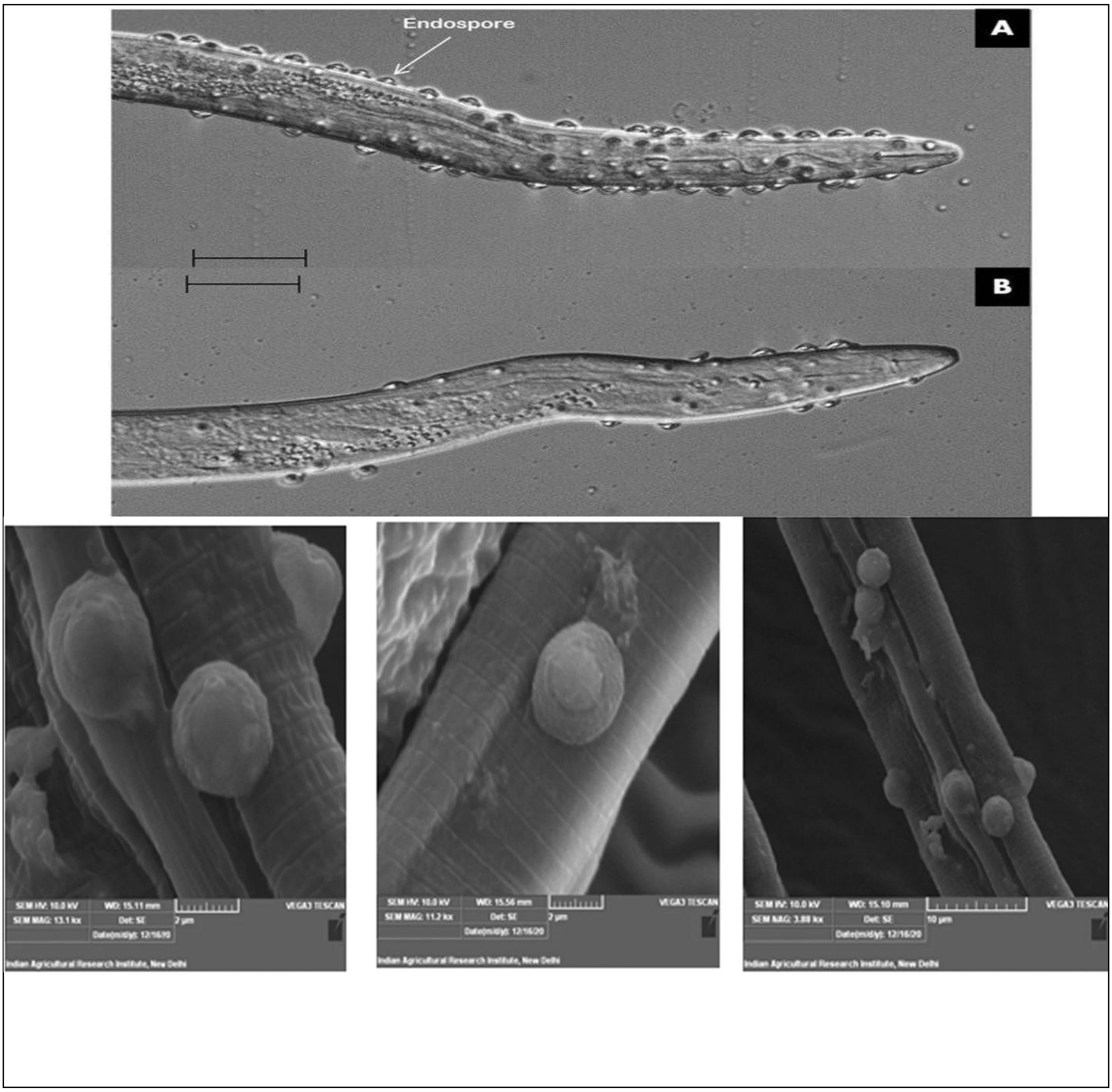


Fig. 20. Role of bacterial bioagent, *Pasteuria penetrans* in the management of root knot nematode, *Meloidogyne incognita* (Jagadeeswaran et al., 2024)

The hypovirulence is a well-known example of virus that infects the pathogenic fungus that causes chestnut blight (chestnut blight canker disease) in *Cryphonectria parasitica* trees. Hypovirulence was found to decrease the pathogen's ability to produce disease. Chestnut blight has been managed in various locations by hypovirulence phenomena (Milgroom and Cortesi 2004; Tripathi et al., 2023).

However, the way viruses, fungi, trees, and the environment interact determines whether hypovirulence is successful or not.

Fig. 21. Comparison of Hypovirulent and virulent strains of *Cryphonectria parasitica* and their morphological and biochemical Characteristics (a) Healed chestnut blight canker indicative of *Cryphonectria parasitica* hypovirulence. (b) Virulent chestnut blight canker. (c) Culture morphology of *C. parasitica* isolates: CHV1-infected YL-10 (white) and (d) CHV1-free EU-1 (orange) on PDA. (e) Bavendamm assay: brown coloration corresponds to polyphenol oxidase activity of the wild-type EU-1 isolates, while the weak color change in YL-10 suggests potential hypovirulence (Çelik et al., 2024)

In contrast, hyperparasitism is another mechanism of biocontrol of pathogenic microbes. In this process microbial agent parasites on another microbe. Sometimes it targets an individual fungal pathogen. For example, powdery mildew pathogens were parasitized by a small fungal group, including *Acrodontium crateriforme*, *Acremonium alternatum*, *Ampelomyces quisqualis*, *Cladosporium oxysporum*, and *Gliocladium virens* (Kiss 2003; Tripathi et al., 2023).

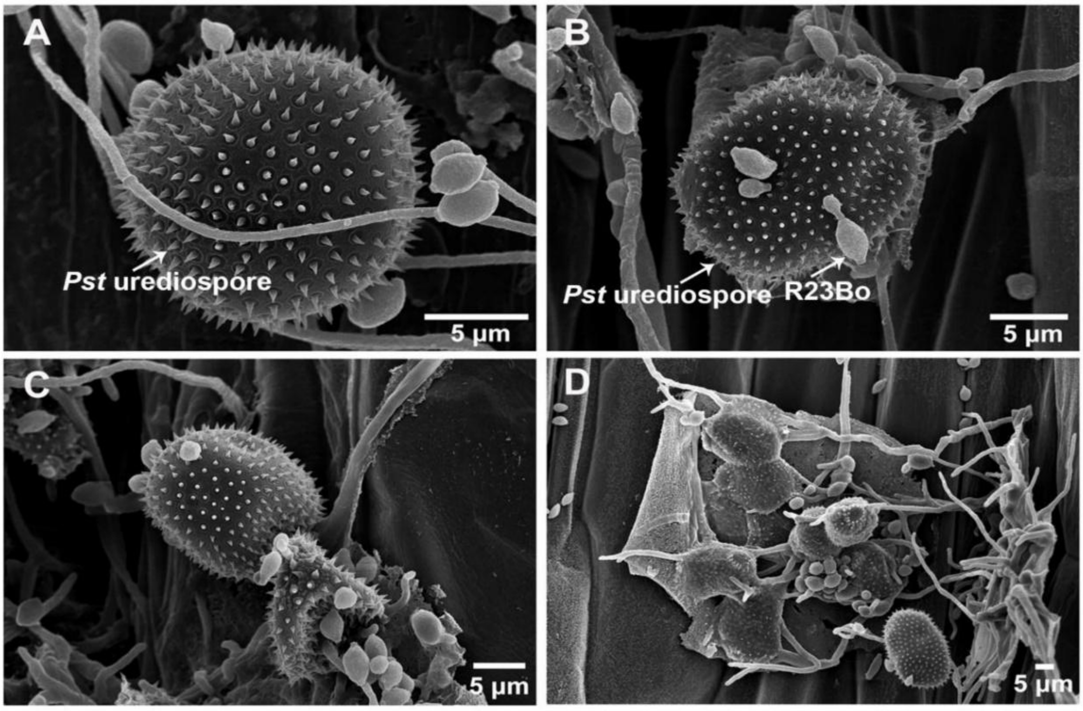


Fig. 22. The hyperparasite *Cladosporium cladosporioides* isolate parasitized on *Puccinia striiformis* f. sp. *tritici* (*Pst*) urediospores and uredinium. (**A**), urediospores of the *Pst* before *C. cladosporioides* was parasitized (×4000). (**B**–**D**), At the early hyperparasitic stage, the urediospores were shriveled (×3000, ×2200, ×1000, respectively) (Zhang, et al., 2022).

Many plant-pathogenic fungal species such as *Coniothyrium minitans* have been identified to attack sclerotia, while others such as *Pythium oligandrum* attacks living hyphae. In this context, *Paecilomyces lilacinus* and *Dactylella oviparasitica* parasite on various growth stages of phytopathogenic nematodes. In contrast to hyperparasitism, microbial predation is more general and nonspecific to pathogen and has less predictable effects on disease control. In contrast to normal growing conditions, certain species exhibit predatory behavior when there is a shortage of nutrients. To paralyze *Rhizoctonia saloni*, certain *Trichoderma* species exhibit a distinct reaction by activating the chitinase genes, which encodes the upregulation of chitinase enzymes which degrades the fungal cell wall (Mohamed et al., 2021).

6.2. Antibiotic-Mediated Suppression

Antibiotics are classified as microbial toxins, which cause minuscule amounts of harm or death to various other organisms. Certain bacteria are thought to be a significant source of generating and secreting one or more antibacterial chemicals that effectively suppress plant pathogens that cause diseases. including nonvolatile antibiotics like polyketides (diacetylphloroglucinol (DAPG) and mupirocin). Volatile antibiotics like hydrogen cyanide, aldehydes, alcohols, ketones, and sulphides, and heterocyclic nitrogenous compounds like phenazine derivatives (pyocyanin, phenazine-1-carboxylic acid; PCA, PCN, and hydroxyphenazines) (de Soussa et al., 2003; Tripathi et al., 2023) Numerous lipopeptide antibiotics, including iturins, bacillomycin, surfactin, and Zwittermicin A, are produced by *Bacillus strains*.

In vitro/in situ, the use of antibiotics has significantly inhibited the growth of the target microorganisms. In situ antibiotic synthesis can be facilitated by a variety of biocontrol agents (Pal and McSpadden 2006; Mohamed et al., 2021). *Pseudomonas fluorescens* is one of the biocontrol bacteria that create volatile chemicals like hydrogen cyanide (HCN) in addition to polyketides and lipopeptides. By interfering with the pathogens' cellular respiration, HCN efficiently suppresses disease like Thielaviopsis basicola-induced black root rot (Junaid et al., 2013; Babbal et al., 2017).

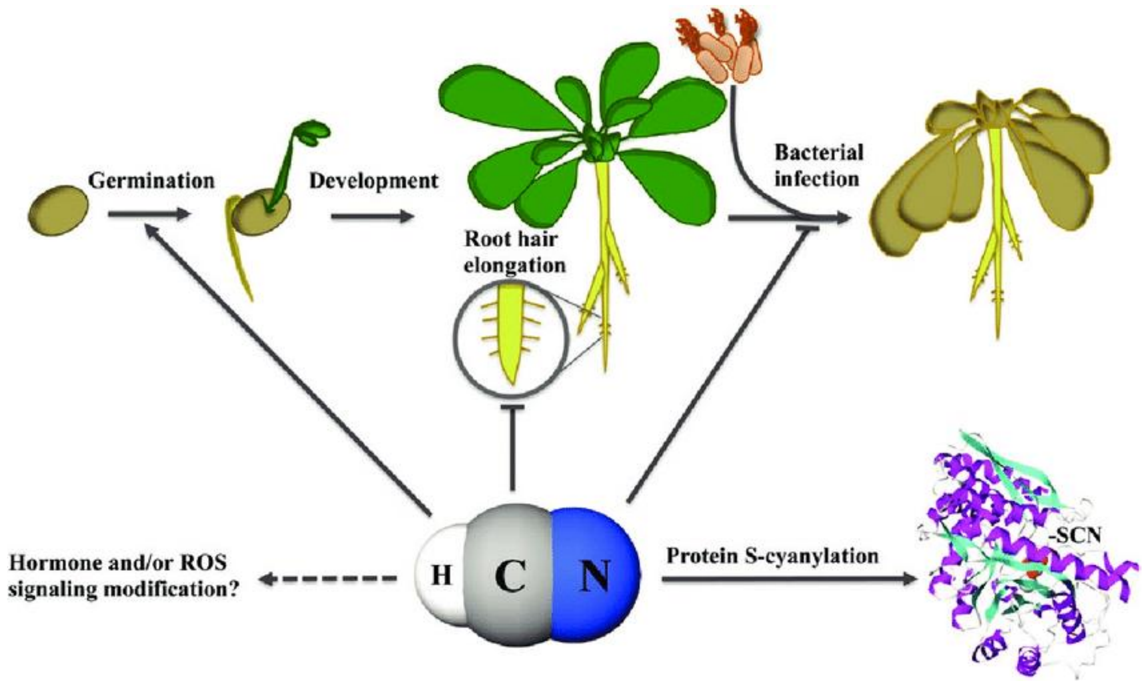


Fig. 23. Hydrogen cyanide (HCN) influences plant processes by inducing germination, inhibiting root hair elongation, and modulating defense mechanisms through confirmed and proposed pathways like S-cyanylation and ROS signaling (Gotor et al., 2019).

6.3. Lytic enzymes and other by-products of microbial life:

One of the main methods by which biocontrol agents manage soil-borne diseases is lysis. This includes the synthesis of metabolites or enzymes that break down cell walls. A vast range of polymeric substances, such as chitin, proteins, cellulose, hemicellulose, and DNA can be hydrolyzed by the lytic enzymes released by various microbes (Singh et al., 2020). Plant pathogen activity can be directly suppressed by the expression and secretion of these enzymes by various microorganisms. *Pseudomonas fluorescens* and *Bacillus* species are examples of plant growth-promoting *rhizobacteria* (PGPR) that can produce strong lytic enzymes, antibiotics, and systemic resistance in plants against a range of plant pathogenic diseases. These include cellulase, protease, β-1,3-glucanase, and chitinase, all of which have potent lytic activity (Singh et al., 2020). By attacking the structural integrity of the fungal infections' cell walls, these enzymes directly impede the growth of their hyphae. Some biocontrol agents, such as *Pseudomonas fluorescens* and *Bacillus*, are particularly effective in producing these enzymes (Junaid et al., 2013; Singh et al., 2020).

6.4. Cyanobacteria and allelopathy

Allelopathy is a phenomenon in which bioactive substances released by organisms, affecting the growth and survival of other cyanobacteria. This phenomenon plays a vital role in the biological management of plant diseases. For instance, it has been demonstrated that *methylisoborneol* (MIB), which is generated by cyanobacteria like *Nostoc* spp., inhibits the bacterial pathogen *Ralstonia solanacearum* (Pandit et al., 2022). The word "allelopathy," derived from the Greek words "allelo" (mutual) and "pathy" (suffering or effect), refers to the chemical interactions that take place when one organism releases bioactive substances that have an impact on the development, survival, or reproductive potential of another (Kostina-Bednarz et al., 2023). Numerous secondary metabolites with antifungal, antibacterial, and herbicidal qualities are produced by cyanobacteria, including cyanobacterin and volatile organic compounds (VOCs) including methylisoborneol (MIB) and geosmin. Molisch's concept was expanded and used in practice to describe chemical interactions and communication between different organisms in general (Kostina-Bednarz et al., 2023; Singh et al., 2020). Cyanobacteria contribute significantly to the biological control of several plant diseases through the following approaches.

1. Production of antimicrobial compounds: Some cyanobacteria generate bioactive compounds that have antibacterial and antifungal qualities. These compounds can stop plant diseases from growing (Righini and Roberti 2019).
2. Induction of plant resistance: by strengthening defenses against various diseases, cyanobacteria can help plants become more resilient (Righini and Roberti 2019).
3. Competition for resources: Cyanobacteria restrict the establishment and growth of pathogenic microbes by entering the rhizosphere and colonizing plant surfaces, where they compete with pathogens for nutrients and space (Pandit et al., 2022).

4. Soil fertility improvement: By fixing nitrogen and producing biofertilizers, cyanobacteria help to improve soil fertility, which encourages healthier plant development and lessens disease susceptibility. The potential of cyanobacteria as sustainable agents in integrated plant disease management methods is shown by these complex interactions (Jose et al., 2024). Through nitrogen fixation, cyanobacteria such as *Anabaena* have also been demonstrated to increase soil fertility, greatly increasing wheat yield in field tests (Jose et al., 2024).

7. Challenges of using cyanobacteria and seaweeds in crop protection:

1- Limited or uncertain demand of seaweeds (Cai et al.,2021). Most seaweeds are farmed at the water's surface to ensure adequate sunlight for photosynthesis; hence, they are typically grown in nearshore regions for operational and logistical efficiency. Nearshore operations generally incur lower investment and operational expenses.

2- Shortage of labour (Liu et al., 2019). Seaweed cultivation typically requires substantial labour for planting, daily maintenance, harvesting, and post-harvest processing, with a seasonal or intermittent demand (e.g., a significant workforce is necessary for a brief period to harvest seaweeds at the optimal time to ensure quality).

3- Constraints over integrated farming systems (Campbell et al., 2019). A recent study on the viability of integrated multitrophic aquaculture (IMTA) in Europe identified limitations across multiple dimensions, including biological, conflicts, environmental, interest, legislative, market, operational, research and development, and vandalism (Kleitou et al., 2018).

4- Low or declined seedling quality (Hu et al., 2021). The quality of seedlings has become increasingly vital in the context of deteriorating agricultural conditions, including elevated ocean temperatures and more frequent and severe disease outbreaks. Outsourcing high-quality seed stocks from specialized hatcheries is a prevalent practice in aquaculture; however, integrating this business model may pose challenges for certain seaweeds (e.g., Kappaphycus/Eucheuma) cultivated by numerous smallholder farmers who can readily acquire cultivars via vegetative propagation from their own harvests.

5- Environmental and ecosystem impacts and risks (Campbell et al., 2019). Seaweeds and cyanobacteria as extractive aquaculture species are generally more environmentally sustainable than fed aquaculture species. Improperly managed seaweed cultivation may adversely impact the environment or ecosystem by (1) disseminating diseases and parasites; (2) releasing reproductive materials from domesticated or non-native species that could compromise the genetic integrity of local species; (3) impeding water flow, which may disrupt sediment transport and alter marine chemistry; (4) competing for light and nutrients with other marine organisms; (5) causing environmental degradation through the construction of farming systems (e.g., destroying mangroves for wooden stakes or damaging the benthic ecosystem by clearing the sea floor or utilising stakes or anchors); and (6) generating pollution during operations (e.g., loss or disposal of cultivation materials or noise generation) (Campbell et al., 2019).

8. Conclusion

In conclusion, the increasing challenges in food security, coupled with the adverse effects of traditional agricultural practices, underscore the need for sustainable alternatives. The use of bioproducts such as macroalgae, microalgae, and cyanobacteria as biocontrol agents for management of plant phytopathogens and pest invasion offers promising solutions for enhancing agricultural productivity while minimizing environmental impacts. These organisms act as effective biocontrol agents by suppressing pathogens by variable mechanisms and improving nutrient uptake, thus reducing reliance on chemical pesticides. They are also rich sources of bioactive compounds like phytohormones and antioxidants, which promote plant growth and bolster defences against diseases. Additionally, their ability to fix nitrogen and enhance soil health further contributes to sustainable farming practices. However, further research is essential to optimize their applications and understand their ecological interactions. Overall, integrating algae and cyanobacteria into agricultural practices represents a critical step toward achieving a more resilient and environmentally friendly agricultural ecosystem.

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