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Spirulina-based approaches for the control of soil-borne pathogens: Mechanism and future perspective

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Abstract

Soil-borne pathogens are a big problem for farming since they cause big losses in crop yields around the world. *Fusarium oxysporum*, *Rhizoctonia solani*, and *Pythium ultimum* are examples of pathogens that stay in the soil for a long time, making them hard to control. Root-knot nematodes (*Meloidogyne* spp.) are also hard to control. Traditional chemical pesticides work for a short time, but they cause major health and environmental problems, such as resistance and ecological imbalance. So, we need more and more sustainable options.

Spirulina platensis (also known as *Arthrospira platensis*) is a filamentous cyanobacterium that has a lot of bioactive chemicals, like phenolics, polysaccharides, fatty acids, and pigments. This makes it a good candidate for biocontrol. These chemicals are very good at killing germs, protecting plants from damage, and helping them flourish. Studies have demonstrated that *Spirulina* extracts stop microbes from growing by breaking down cell membranes, messing up metabolic processes, and stopping biofilm formation. This review talks about how *Spirulina* can help reduce soil-borne infections. It focuses on how it works, what experiments have shown, and what the future holds. Even while tests in labs and greenhouses show promise, more testing in the field and development of the formulation are needed. Using *spirulina* as a base for disease management in modern agriculture is a long-lasting and environmentally beneficial way to do it.

Keywords: *Spirulina platensis*, soil-borne pathogens, biocontrol agents, microalgae, plant disease management, sustainable agriculture, antimicrobial activity, induced systemic resistance, rhizosphere interactions, bioactive compounds

Introduction

Soil-borne infections are one of the biggest problems for global agriculture because they cause big drops in crop yields and put food security at risk. These pathogens comprise a diverse range of fungi, oomycetes, bacteria, and plant-parasitic nematodes that infect plant roots and lower stems, causing diseases such as damping-off, root rot, and vascular wilt. *Fusarium oxysporum*, *Rhizoctonia solani*, *Pythium ultimum*, and root-knot nematodes (*Meloidogyne* spp.) are some of the most economically important pathogens. These pathogens can live in soil for a long time by forming resistant structures like chlamydospores, sclerotia, and cysts (Dean et al., 2012; Savary et al., 2019) [4, 3].

Soil-borne diseases are hard to control because they stay in the soil for a long time and can infect a wide range of plants. Synthetic fungicides and nematicides are a big part of traditional management methods since they quickly and effectively kill infections. But using these chemicals too much and for too long has caused a number of bad effects, such as the emergence of resistant pathogen strains, the destruction of helpful soil microbiota, pollution of the environment, and possible health risks for people (Popp et al., 2013; Aktar et al., 2009) [2, 1]. The necessity for eco-friendly alternatives has become even more important because of stricter rules on pesticide use and the increased need for sustainable farming methods.

Biological control tactics have been very popular in the last few years as long-term ways to deal with plant diseases. Microalgae and cyanobacteria have emerged as prospective sources of bioactive chemicals with antibacterial and plant growth-promoting effects. *Spirulina platensis* (also known as *Spirulina platensis*) *Arthrospira platensis*, a filamentous, photosynthetic cyanobacterium, has been extensively grown for its significant nutritional value, comprising roughly 60–70% protein, vital amino acids, vitamins, minerals, and pigments (Habib et al., 2008; Becker, 2013) [17, 18].

Spirulina has shown great promise in agriculture since it has a lot of different bioactive chemicals, such as phenolic compounds, polysaccharides, fatty acids (like gamma-linolenic acid), and pigments (like phycocyanin). These chemicals have strong antibacterial, antioxidant, and immunomodulatory capabilities that can help stop plant infections and make plants better at defending themselves (Wu et al., 2016; Zainab et al., 2020) ^[20, 21]. Research indicates that Spirulina extracts can impede the proliferation of several bacterial and fungal pathogens by compromising cell membranes, affecting metabolic functions, and producing oxidative stress within microbial cells (El-Sheekh et al., 2014; Metekia et al., 2023) ^[24, 23].

Spirulina not only kills germs directly, but it also works as a biostimulant to help plants develop and make soil healthier. It increases the availability of nutrients, encourages beneficial microbial activity in the rhizosphere, and triggers systemic resistance in plants by activating defense-related pathways such as jasmonic acid and ethylene signaling (Khan et al., 2009; Colla et al., 2015) ^[15, 14]. Because Spirulina has so many uses, it could be a good addition to long-term disease management plans.

Even if there is more and more studies showing that Spirulina could be useful in farming, it is still too early to use it to get rid of soil-borne diseases. Most research has occurred in laboratory or greenhouse settings, with minimal field validation. Moreover, issues concerning the standardization of extraction techniques, formulation advancement, and extensive production persist and require resolution.

Consequently, this review seeks to deliver an extensive examination of Spirulina-based methodologies for the management of soil-borne diseases. It emphasizes the mechanisms of action, experimental evidence, and future prospects, aiming to underscore its potential contribution to sustainable and environmentally friendly agriculture.

2. Overview of *Spirulina platensis*

Taxonomy and General Traits

Spirulina platensis (also known as *Arthrospira platensis*) is a filamentous, photosynthetic cyanobacterium that belongs to the order *Oscillatoriales*. It is often found in alkaline and saline bodies of water, where it does well in high pH and temperature conditions. Spirulina is grown on a large scale for use as a dietary supplement and functional food because it grows quickly and can adapt to many environments (Habib et al., 2008; Becker, 2013) ^[17, 18].

Morphologically, Spirulina has multicellular, spiral-shaped filaments termed trichomes, which are devoid of a genuine nucleus and membrane-bound organelles, typical of prokaryotic organisms. It is an environmentally friendly source of biomass since it can do oxygenic photosynthesis and fix carbon dioxide (Vonshak, 1997) ^[19].

Spirulina biomass is highly prized for its remarkable nutritional composition, comprising around 60–70% protein, along with important amino acids, vitamins (B-complex, vitamin E), minerals (iron, calcium), and pigments such as chlorophyll and phycocyanin (Becker, 2013; Habib et al., 2008) ^[17, 18].

Bioactive Compounds and Their Functional Roles

Spirulina's biological potential is mostly due to the wide spectrum of bioactive chemicals it contains. These chemicals are very important for fighting germs, protecting against oxidation, and helping plants thrive.

Spirulina platensis contains a wide range of bioactive chemicals, such as phenolic compounds, flavonoids, pigments, polysaccharides, fatty acids, and secondary metabolites. These molecules work together to make it antibacterial and protect plants. Spirulina contains phenolic chemicals and flavonoids that are very good at fighting off bacteria and free radicals. They do this by breaking down microbial cell membranes, stopping enzymes from working, and getting in the way of nucleic acid synthesis (El-Sheekh et al., 2014; Alshuniaber et al., 2021) ^[23, 22]. Phycocyanin is one of its pigments that is very important since it is a strong antioxidant, anti-inflammatory, and antibacterial agent. It does this by scavenging reactive oxygen species (ROS) and protecting plant cells from oxidative stress (Wu et al., 2016) ^[20]. Polysaccharides from Spirulina are also known to boost plant immune responses and activate defensive mechanisms. They also improve microbial activity in the soil and encourage positive interactions in the rhizosphere (Khan et al., 2009) ^[14]. Essential fatty acids, such as gamma-linolenic acid (GLA), also help it fight germs by breaking down pathogen cell membranes and stopping their proliferation (Colla et al., 2015) ^[15]. Spirulina also makes a number of secondary metabolites, such as antimicrobial peptides and alkaloids, that make it better at fighting plant diseases and making plants more resistant (Zainab et al., 2020) ^[21]. Together, these bioactive constituents make Spirulina a multifunctional biocontrol agent with significant potential in sustainable agriculture.

Table 1: Bioactive compounds of *Spirulina platensis* and their roles in disease control

Compound	Source in Spirulina	Function	Role in Disease Control
Phenolics	Cell extract	Antimicrobial	Disrupt pathogen membranes
Phycocyanin	Pigment	Antioxidant	Reduces ROS stress in plants
Polysaccharides	Cell wall	Immune stimulation	Induces plant defense
Fatty acids (GLA)	Lipid fraction	Antimicrobial	Inhibits fungal growth
Proteins/Peptides	Biomass	Enzyme inhibition	Suppresses pathogens

Antimicrobial and Antioxidant Qualities

Many studies have shown that Spirulina has high antibacterial properties against a wide spectrum of microorganisms, such as bacteria and fungi. The antibacterial activity is mainly due to the synergistic effects of its bioactive chemicals, which attack many cellular processes in pathogens (El-Sheekh et al., 2014) ^[23].

Spirulina has strong antioxidant properties that assist lower oxidative stress in plants that have been infected by pathogens. Phycocyanin, phenolics, and vitamins in its

biomass are mostly what give it this antioxidant power (Wu et al., 2016) ^[20].

Function as a Biostimulant in Farming

People are interested in spirulina as a natural biostimulant since it can help plants grow and make soil healthier. It can be used to improve soil, treat seeds, or spray on leaves.

Some of the main benefits are:

- Better germination of seeds and development of plants

- Better absorption and use of nutrients
- More chlorophyll and better photosynthesis
- Encouraging helpful soil microbes

These benefits are linked to the presence of growth-promoting chemicals, including amino acids, vitamins, and phytohormone-like molecules (Khan et al., 2009; Colla et al., 2015) ^[15, 14].

Role in Making Soil Healthier

Spirulina helps the soil stay healthy by making more types of microbes and nutrients available. It helps good bacteria flourish, which fight diseases and lower their numbers in the rhizosphere.

Spirulina can also make the soil structure and organic matter content better, which helps water stay in the soil and nutrients move around (Singh et al., 2011) ^[13].

Possible use as a biocontrol agent

Spirulina is a good choice for biocontrol applications since it has antibacterial, antioxidant, and plant growth-promoting qualities. It can work through more than one route, which is better than traditional chemical pesticides, which usually only work through one way.

Recent research indicates that Spirulina can be incorporated into sustainable farming practices within integrated pest management (IPM) frameworks, hence decreasing dependence on synthetic insecticides (Colla et al., 2015) ^[15].

3. Pathogens that live in the soil and how they affect farming

Soil-borne pathogens are a wide range of microorganisms, such as fungus, oomycetes, bacteria, and plant-parasitic nematodes, that live in the soil and infect the roots and lower stems of plants. These diseases cause huge losses in agriculture around the world by lowering the quality and quantity of crops. Their capacity to endure in soil for protracted durations via resilient formations such spores, sclerotia, and cysts renders them especially challenging to control (Dean et al., 2012; Savary et al., 2019) ^[4, 3].

Main Types of Pathogens in Soil

Fungal Pathogens

Fungal infections are some of the most harmful soil-borne organisms that impact crops. *Fusarium*, *Rhizoctonia*, and *Sclerotium* are some of the most important genera.

Fusarium oxysporum is a well-known vascular wilt pathogen that may infect many different types of plants, including tomatoes, bananas, and legumes. It settles in the xylem vessels, which stops water from moving and causes withering symptoms (Dean et al., 2012) ^[4]. *Rhizoctonia solani* also causes damping-off and root rot infections, especially in seedlings. This makes it hard for plants to grow and can cause them to lose yield (Okubara et al., 2014) ^[8].

Sclerotium rolfii makes resistant structures called sclerotia that let it live in bad weather and infect several host plants (Punja, 1985) ^[9]. These fungi are quite adaptive and may grow well in many different types of soil.

Pathogens of Oomycetes

Oomycetes, sometimes known as water molds, are fungus-like creatures that can make plants very sick, especially when the soil is wet.

Pythium ultimum is a primary cause of damping-off in seedlings, which quickly breaks down the tissue and kills the plant (Van der Plaats-Niterink, 1981) ^[10]. Oomycetes create zoospores that can move around, which helps them spread quickly in soils that are wet (Kamoun et al., 2015) ^[7].

Nematodes

Plant-parasitic nematodes are tiny roundworms that attack plant roots and make it harder for plants to get nutrients.

Root-knot nematodes (*Meloidogyne spp.*) are some of the most significant nematodes for the economy. They make galls on roots, which makes it harder for plants to take in water and nutrients (Jones et al., 2013) ^[6]. Plants that are infested often don't grow as well, become yellow, and produce less fruit.

Nematodes can also work along with fungal pathogens to make diseases worse and make management more difficult.

Bacterial Pathogens

Some bacteria that live in soil can also cause plant diseases, but they are not as common as fungi and nematodes.

Ralstonia solanacearum is a well-known bacterium that makes crops like tomatoes and potatoes wilt. It gets into the vascular system and kills plants quickly (Mansfield et al., 2012) ^[5]. These bacteria can live in soil and water for a long time, which makes them hard to regulate.

Symptoms of Disease and Losses in Crops

Soil-borne infections can induce different symptoms in different plants and diseases. Some common signs are:

- Rotting and decaying roots
- Seedlings that are damping off
- Wilting and changes in the color of the vascular system
- Chlorosis and growth that is stunted

These illnesses greatly lower the amount of crops that can be grown, and in the worst circumstances, they can even kill all of the crops. Plant infections are thought to cause yield losses of 20–30% in important crops around the world (Savary et al., 2019) ^[3].

Staying Alive and Lasting in Soil

One of the biggest problems with controlling soil-borne diseases is that they can live in soil for a long time.

- Making structures that are resistant, like chlamydospores, sclerotia, and cysts Staying alive in contaminated plant detritus
- A wide range of hosts that lets infection cycles go on and on

These survival tactics let infections stay alive even when there are no host plants, which makes it hard to get rid of them (Dean et al., 2012) ^[4].

Problems with Traditional Control Methods

People have always employed chemical fungicides and nematicides to keep illnesses from spreading in the soil. These strategies work well in the near term, however they have several problems:

- Creation of disease strains that are resistant
- Harmful impacts on creatures that aren't the goal
- Pollution of the environment from chemical leftovers
- High costs and rules that make it hard to do business

Too much usage of chemical pesticides has also harmed the health of the soil and reduced the number of helpful microbes (Aktar et al., 2009; Popp et al., 2013) ^[2, 1].

The Need for Long-Term Disease Control

The shortcomings of traditional approaches underscore the necessity for sustainable and environmentally friendly alternatives. Using natural materials and microorganisms for

biological control has become a promising method.

Cyanobacteria like *Spirulina platensis* have a lot of potential since they can make bioactive substances that kill diseases, boost plant defenses, and balance the microbial community in the soil. These characteristics render *Spirulina* an appropriate option for incorporation into sustainable agricultural methodologies and integrated pest management frameworks (Colla et al., 2015) ^[15].

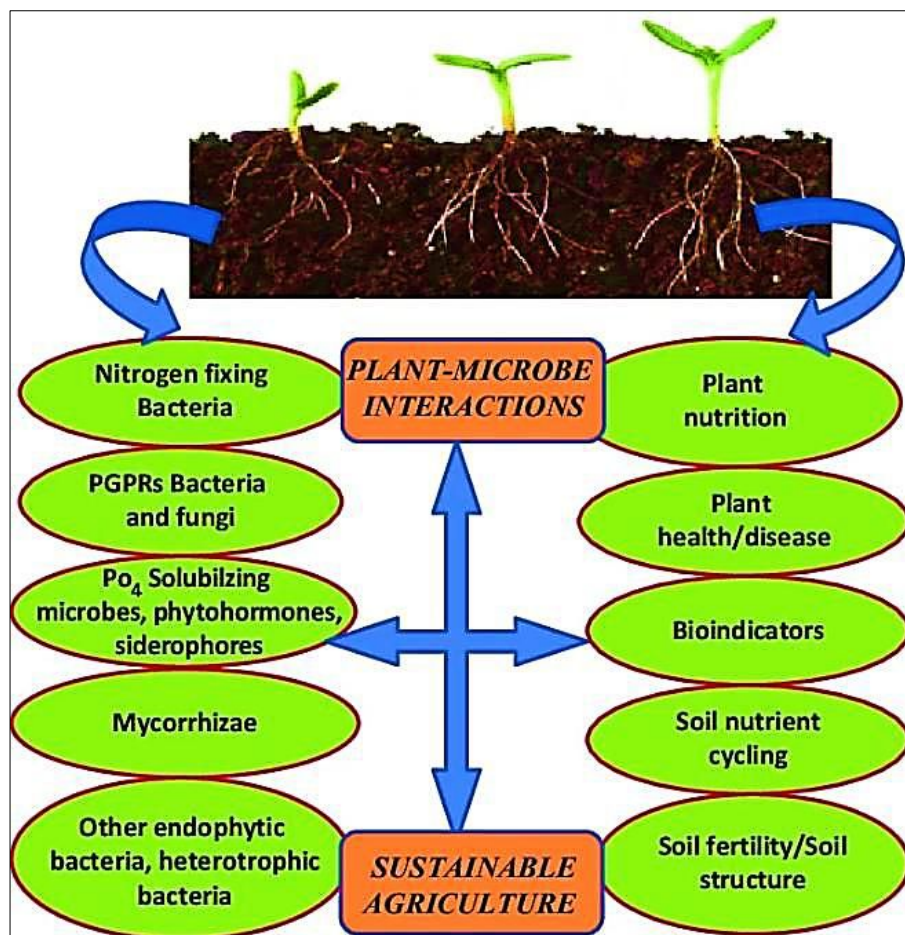


Fig 1: Beneficial plant–microbe interactions supporting plant growth, soil health, nutrition, and disease resistance in sustainable agriculture.

This figure shows how beneficial plant–microbe interactions support plant growth and soil health. These interactions play a key role in achieving sustainable agriculture by improving nutrition and disease resistance.

4. Mechanisms of *Spirulina platensis* in the Control of Soil-Borne Pathogens

Spirulina platensis works as a biocontrol agent because it can work through several different but complementary ways. Conventional chemical pesticides usually work by targeting one biochemical pathway. *Spirulina*, on the other hand, has a wide range of actions, including direct antibacterial activities, triggering plant defense responses, antioxidant activity, and changing the microbial communities in the rhizosphere. These many ways of working together make it a good choice for a long-term way to control soil-borne diseases.

Direct Antimicrobial Activity

One of the main ways *Spirulina* stops infections from spreading in the soil is by killing them directly. *Spirulina* has bioactive ingredients such as phenolics, fatty acids,

flavonoids, and antimicrobial peptides that stop pathogens from growing and living.

These chemicals can:

- Break down the cell membrane's structure
- Make the membrane more permeable
- Make things leak out of cells
- Stop important enzymatic activity

Research has shown that *Spirulina* extracts have strong effects against fungal infections including *Fusarium oxysporum* and *Rhizoctonia solani*, slowing down the growth of mycelium and the germination of spores (El-Sheekh et al., 2014; Metekia et al., 2023) ^[24, 23]. The antibacterial activity is frequently concentration-dependent and changes according to extraction procedures and solvent systems.

Ways to Fight Fungi

Spirulina has significant antifungal properties that work in a number of ways to stop fungi from growing and developing.

- Stopping spores from germinating, which stops the first infection

- Stopping hyphal extension and fungal colonization
- Disruption of the production and integrity of fungal cell walls

It is known that phenolic chemicals and fatty acids in

Spirulina can stop fungi from growing by messing with their metabolism and stopping the enzyme systems they need to flourish (Alshuniaber et al., 2021) ^[22]. These factors together make soil-borne fungus less harmful and less likely to spread.

Table 2: Mechanisms of Action of Spirulina

Mechanism	Description	Target
Direct antimicrobial	Membrane disruption, enzyme inhibition	Fungi, bacteria
Antifungal activity	Spore germination inhibition	Fusarium, Rhizoctonia
Nematicidal action	Reduces egg hatching	Meloidogyne
ISR (plant defense)	Activates JA & ET pathways	Plant immune system
Antioxidant activity	ROS scavenging	Plant cells
Rhizosphere modulation	Promotes beneficial microbes	Soil ecosystem

Activity that kills nematodes

Spirulina has showed promise in suppressing plant-parasitic nematodes in addition to its antifungal capabilities.

Research shows that Spirulina extracts can

- Lower the number of *Meloidogyne spp.* eggs that hatch.
- Stop the growth of young animals
- Reduce the ability of nematodes to move and spread disease

These effects are due to toxic metabolites and fatty acids that mess up the nematode's normal functions (Khalil & El-Ashry, 2012) ^[12]. This means that Spirulina could be a useful part of a plan to control nematodes in a more general way.

Starting Plant Defense Mechanisms

One of the best things about Spirulina is that it can boost a plant's natural defense through induced systemic resistance (ISR).

Using Spirulina makes:

- The activity of enzymes that help protect the body, such peroxidase (POD) and polyphenol oxidase (PPO)
- Building up of phenolic compounds
- Making phytoalexins

These molecular changes make plants better at defending themselves and make them less likely to get sick (Khan et al., 2009; Colla et al., 2015) ^[15, 14].

The Function of Plant Signaling Pathways

Spirulina-mediated defensive responses are linked to the activation of plant hormonal signaling pathways, specifically:

- Pathway for jasmonic acid (JA)
- Pathway for ethylene (ET)

These pathways control how plants react to necrotrophic diseases and help them build up systemic resistance. When these pathways are turned on, defense-related genes are expressed more strongly, and plants become more resilient (Pieterse et al., 2014) ^[11].

Responses at the Molecular Level

At the molecular level, Spirulina affects how genes that help plants fight off stress and protect themselves are turned on and off.

Some important molecular responses are:

- Increased activity of UDP-glucose glycosyltransferase (UDPGT), which is involved in making phytoalexins
- Activation of protein kinases that are part of signal transduction
- More cytochrome P450 enzymes are made to help in detoxification
- Increased activity of peroxidases for scavenging reactive oxygen species (ROS)

These molecular modifications help plants become more resistant and make diseases less severe (Zhang et al., 2019) ^[29].

Antioxidant Activity and Regulation of ROS

Plants often experience oxidative stress when pathogens infect them because they make too many reactive oxygen species (ROS). Spirulina has strong antioxidants including phycocyanin, phenolic compounds, and vitamins that help with:

- Getting rid of extra ROS
- Keeping cells safe from oxidative damage
- Keeping cells in balance

This antioxidant activity is very important for reducing stress and helping plants survive when pathogens attack (Wu et al., 2016) ^[20].

Changes in the Rhizosphere and Interactions between Microbes

Spirulina helps keep diseases at bay by making the microbial dynamics in the rhizosphere better.

- Encourages helpful microbes like PGPR
- Increases the variety of microbes
- Stops harmful populations from growing by competing with them

A better balance of microbes in the rhizosphere makes it harder for pathogens to thrive and spread (Singh et al., 2011) ^[13].

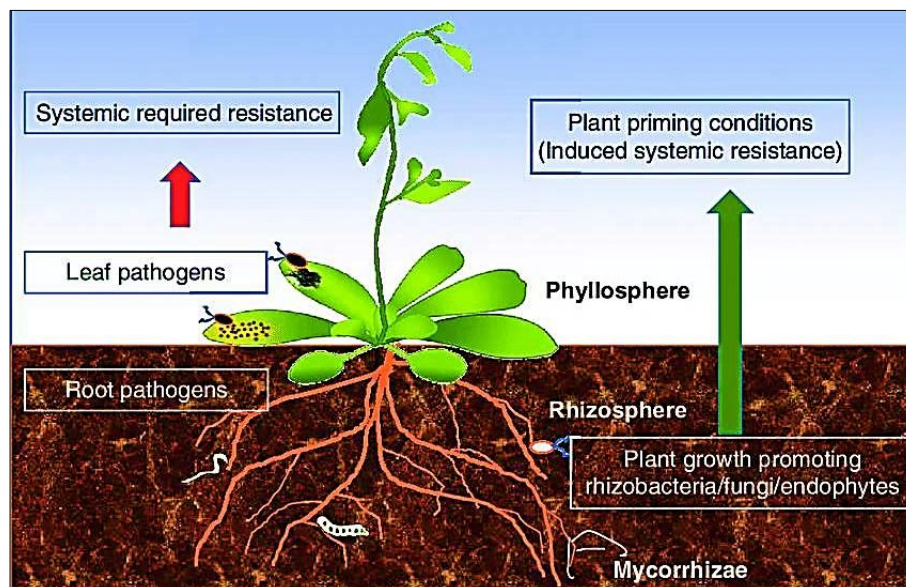


Fig 2: Rhizosphere microorganisms (PGPR and mycorrhizae) enhancing induced systemic resistance (ISR) and plant defense against pathogens.

This image shows how microorganisms in the rhizosphere, such as PGPR and *mycorrhizae*, make plants more resistant to disease (ISR). These interactions make plants better at defending themselves against viruses, keeping both their roots and leaves safe. This makes plants more resistant and healthier overall.

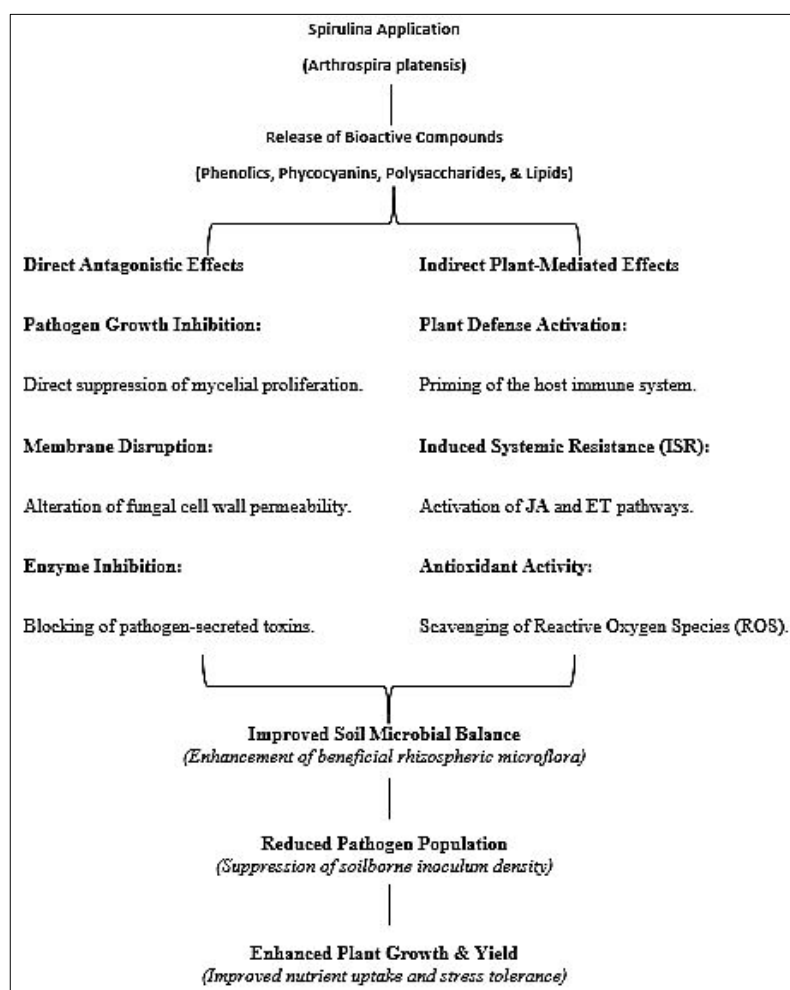
Effects that work together in integrated systems

In integrated pest management (IPM) systems, spirulina can

work well with other biological agents and organic amendments.

- Makes biofertilizers work better
- Works well with Trichoderma and PGPR
- Lessens the need for chemical insecticides

These kinds of integrated techniques help control diseases over the long term (Colla et al., 2015) ^[15].



5. Evidence from case studies and experiments

Many in vitro investigations, greenhouse studies, and a few field trials have looked into the use of *Spirulina platensis* as a biocontrol agent. These studies give solid proof that it can kill bacteria, help plants grow, and maybe even help with long-term disease control. This section presents the most important results from experiments that used *Spirulina*-based treatments to fight soil-borne diseases.

Studies in vitro

In vitro investigations are crucial for assessing the direct antibacterial efficacy of *Spirulina* against phytopathogens. Numerous investigations have indicated that *Spirulina* extracts demonstrate considerable inhibitory effects against

fungus and bacterial infections.

Ethanol and aqueous extracts of *Spirulina platensis* have demonstrated the ability to inhibit the growth of *Fusarium oxysporum*, *Rhizoctonia solani*, and *Pythium ultimum* by decreasing mycelial growth and spore germination (El-Sheekh et al., 2014; Metekia et al., 2023) [24, 23]. The agar well diffusion and poisoned food methods have shown clear inhibition zones, which shows that there are bioactive chemicals that can kill fungi (Ozdemir et al., 2004) [25].

The antibacterial action is frequently concentration-dependent, with elevated concentrations leading to enhanced suppression of pathogen proliferation. These results show that *Spirulina* extracts could be useful as natural antimicrobials.

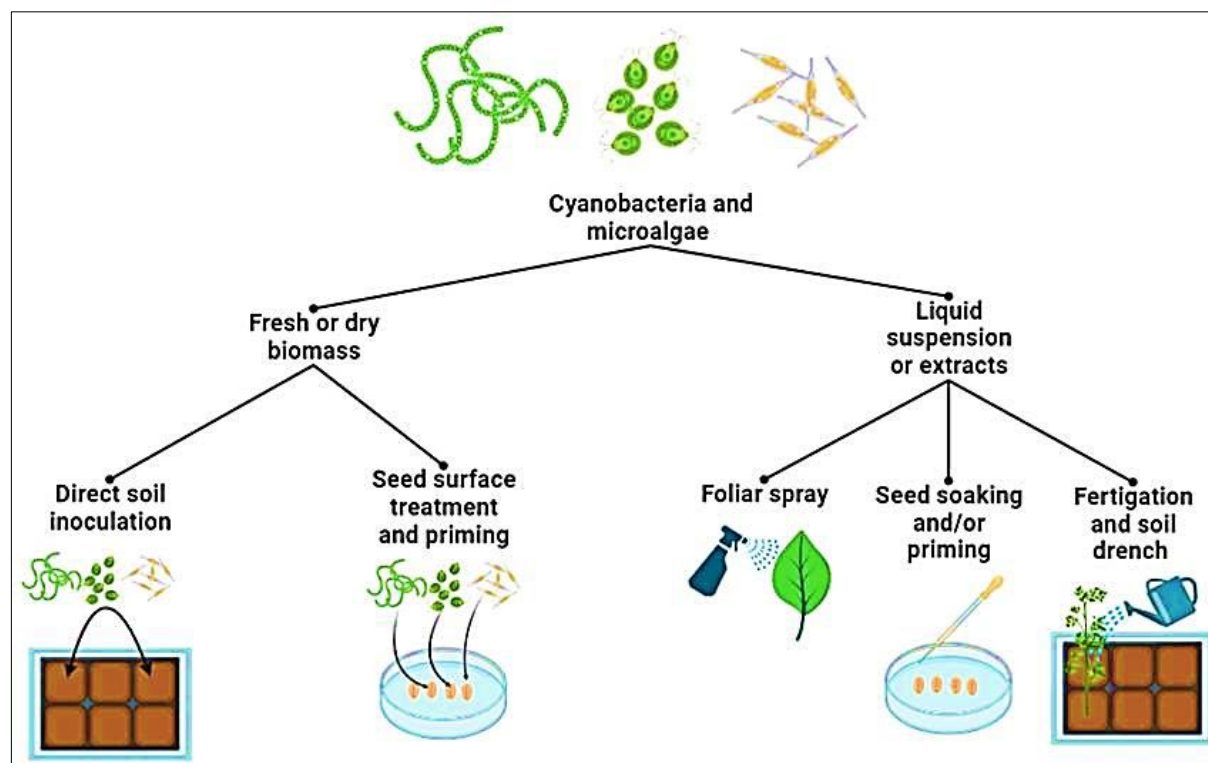


Fig 3: Application methods of *Spirulina platensis* (soil drench, seed treatment, foliar spray) for managing soil-borne diseases.

This diagram shows soil drench, seed treatment/priming, and foliar spray applications using fresh/dried cyanobacterial biomass or liquid suspensions/extracts. These strategies offer bioactive substances to help plants fight soil-borne diseases. The image shows *Spirulina platensis*-based sustainable agriculture methods.

Pot and greenhouse experiments

Greenhouse and pot tests create more realistic circumstances to test *Spirulina*'s plant disease control.

Spirulina biomass or extracts as soil additions or foliar sprays have significantly reduced disease incidence. In tomato plants infected with *Fusarium oxysporum* and *Rhizoctonia solani*, *Spirulina* reduced damping-off and root rot (Abd El-Baky et al., 2016) [26].

Spirulina-treated plants enhanced root length, shoot height, chlorophyll content, and biomass accumulation while suppressing disease (Khan et al., 2009) [14]. These effects are due to antibacterial action and plant defense enhancement.

Field Trials: Although limited, field trials have shown *Spirulina*'s practicality in natural agricultural situations.

Spirulina reduces wilt and root rot diseases in banana and moringa crops, improving plant health and yield (El-Sayed et al., 2015) [28]. *Spirulina* boosted soil fertility and microbial activity in field settings, indirectly supporting plant growth and disease resistance (Singh et al., 2011) [13]. However, environmental heterogeneity and lack of uniform formulations have caused contradictory outcomes, underlining the necessity for larger investigations.

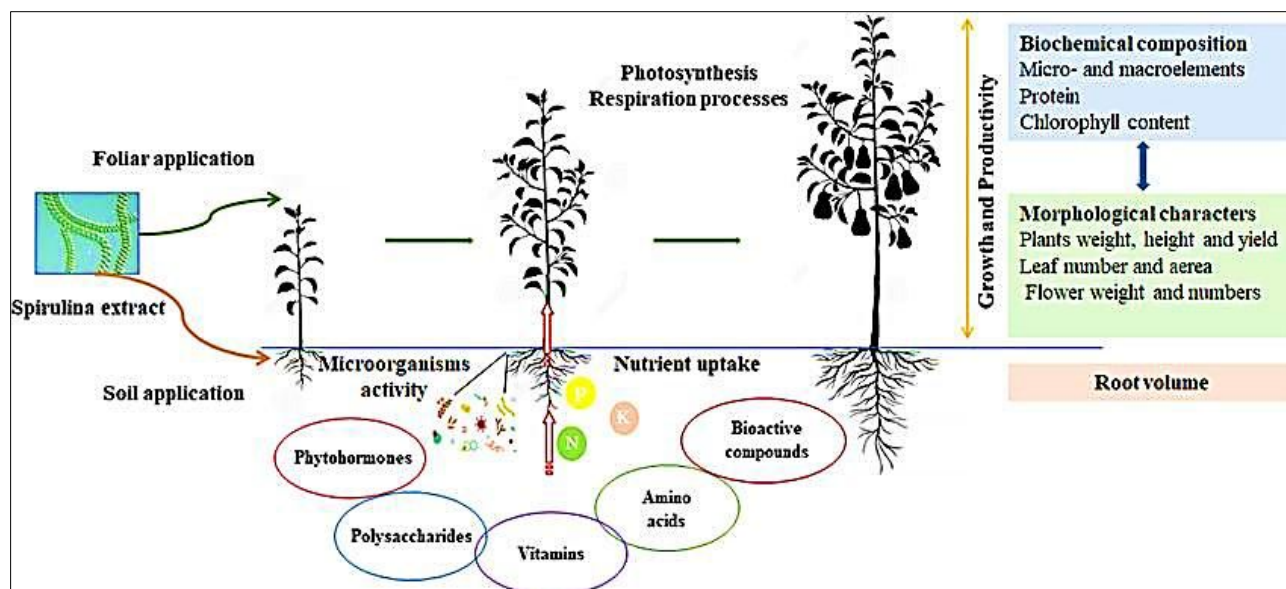


Fig 4: Effect of spirulina extract on plant growth, nutrient uptake, microbial activity, and crop productivity.

There is a correlation between the application of spirulina extract by soil or foliar methods and increased plant growth and productivity, as seen in this image. Microbial activity, nutrient uptake, and the generation of bioactive molecules including phytohormones, vitamins, and amino acids are all stimulated as a result of this. Consequently, the plants exhibit enhanced biochemical composition, shape, and overall yield as a consequence of this.

Impact on Plant-Parasitic Nematodes

Spirulina has demonstrated encouraging efficacy in managing plant-parasitic nematodes, especially *Meloidogyne spp.*

Research indicates that Spirulina treatment diminishes root gall formation, lowers nematode population density, and decreases egg hatching rates (Khalil & El-Ashry, 2012) [12]. These effects are presumably attributable to toxic metabolites and fatty acids that disrupt worm physiology and reproduction.

Moreover, Spirulina augments plant resilience, hence diminishing nematode infestation and harm.

Comparative Analyses with Alternative Biocontrol Agents

Comparative studies have assessed the efficacy of Spirulina in relation to various biological agents and chemical therapies.

Spirulina extracts have antifungal efficacy comparable to certain commercial fungicides against diseases like *Fusarium spp.* (Demir et al., 2006) [27]. Furthermore, when integrated with advantageous microorganisms like *Trichoderma spp.* or plant growth-promoting rhizobacteria (PGPR), Spirulina demonstrated improved disease suppression owing to synergistic interactions (Khan et al., 2009) [14].

The data indicate that Spirulina can be efficiently included into integrated pest control (IPM) systems.

Summary of Key Experimental Findings

Table 3: Summary of Selected Studies on Spirulina-Based Disease Control

Study Type	Crop	Pathogen	Treatment	Key Findings	Reference
In vitro	–	<i>Fusarium oxysporum</i>	Spirulina extract	Reduced mycelial growth	El-Sheekh et al., 2014
In vitro	–	<i>Rhizoctonia solani</i>	Aqueous extract	Inhibited fungal growth	Ozdemir et al., 2004
Greenhouse	Tomato	<i>Fusarium oxysporum</i>	Soil application	Reduced disease severity	Abd El-Baky et al., 2016
Greenhouse	Legumes	<i>Rhizoctonia solani</i>	Spirulina + biofertilizer	Lower root rot incidence	Khan et al., 2009
Field	Banana	<i>Fusarium spp.</i>	Spirulina formulation	Reduced wilt symptoms	El-Sayed et al., 2015
Pot study	Various crops	<i>Meloidogyne spp.</i>	Spirulina extract	Reduced root galling	Khalil & El-Ashry, 2012

Limitations of Current Studies

In spite of the encouraging outcomes, there are still significant limitations:

- The majority of investigations are restricted to circumstances seen in laboratories and greenhouses
- The absence of extraction and application techniques that are fully standardized
- The content of spirulina might vary slightly depending on the conditions under which it is grown
- Short-term and multi-location field investigations that are limited in scope

Due to these constraints, the widespread implementation of spirulina in agricultural settings is hampered.

Research Deficits and Needs for the Future

Additional research is necessary in order to: It is recommended to carry out extensive field tests in a variety of meteorological and agricultural situations.

It is necessary to develop uniform formulations and application methodologies.

- Conduct an analysis of the long-term ecosystem impacts

- Enhance the production facility's cost-effectiveness and its ability to scale

In order to facilitate the commercialization of biocontrol products based on spirulina, solving these gaps will be of great assistance.

6. The Benefits of Using *Spirulina platensis* from a Biocontrol Perspective

Because of the growing worries surrounding the effects that synthetic pesticides have on both the environment and human health, there has been an increase in the investigation of environmentally friendly alternatives for the treatment of plant diseases. Given these circumstances, *Spirulina platensis* has emerged as a potentially useful biocontrol agent due to the fact that it possesses a wide range of functionalities. The benefits of this product go beyond the suppression of pathogens and include enhancements to plant development, soil health, and ecological sustainability.

Eco-Friendly and Sustainable Nature

The fact that spirulina is not harmful to the environment is among the most significant benefits that it offers. Spirulina-based formulations, in contrast to chemical pesticides, are biodegradable and do not leave behind any toxic residues in the soil or water systems.

According to Aktar et al. (2009) ^[1], the utilization of spirulina aids in the reduction of environmental pollution and lessens the possibility of contamination of groundwater and ecosystems that are not the intended targets. In addition, because of its natural nature, it is excellent for use in farming systems that support organic and sustainable practices.

Antimicrobial Activity That Covers a Wide Spectrum

Spirulina possesses antibacterial activity that is broad-spectrum, meaning that it is effective against a wide variety of plant diseases, such as nematodes, bacteria, and fungi.

The bioactive molecules that it contains exert its effects through a variety of methods, hence lowering the probability that pathogen resistance would develop. According to El-Sheekh et al. (2014) ^[23] and Metekia et al. (2023) ^[24], this is a significant benefit over chemical pesticides, which frequently target particular biochemical processes and have the potential to result in the development of resistant strains over time.

Development of Plants That Are More Productive and Grow Faster

In addition to its role as a biocontrol agent, spirulina also

plays a biostimulant role, which means that it encourages the growth and development of plants throughout time.

- Boosts the percentage of seeds that germinate
- Promotes the growth of both trees and plants
- Raise the amount of chlorophyll present and improve the effectiveness of photosynthesis The increase in crop yield According to Khan et al. (2009) ^[14] and Colla et al. (2015) ^[15], these benefits can be linked to the material known as spirulina, which contains amino acids, vitamins, and compounds that are similar to phytohormones.

The Induction of Defense Mechanisms at the Plant Level

Through the activation of defense-related pathways, spirulina significantly improves the resistance of plants to infections. Systemic resistance (ISR) is induced as a result. Increases the activity of enzymes involved in defense Encourages the buildup of substances containing phenolics Pieterse et al. (2014) ^[11] found that this helps to enhance the plant's natural immune system, which in turn lessens the plant's vulnerability to infections.

Enhancement of the Health of the Soil

By increasing the diversity of microorganisms and the availability of nutrients, spirulina makes a substantial contribution to the health of the soil.

- Encourages the growth of beneficial microorganisms in the soil
- Facilitates the cycle of nutrients
- Enhances the structure of the soil and its fertility

According to Singh et al. (2011) ^[13], healthy soil conditions result in an environment that is adverse for the formation of pathogens and support the production of crops in a sustainable manner.

Compatibility with Integrated Pest Management (IPM) Approaches

Spirulina is a versatile ingredient that can be easily incorporated into agricultural techniques that are already in place, notably integrated pest control (IPM) systems.

- Works in conjunction with biofertilizers and bacteria that are beneficial to the environment Reduces reliance on chemical pesticides as a necessary measure
- Contributes to an increase in the performance of illness management methods overall

Spirulina is a versatile tool for sustainable agriculture due to its compliance with agricultural practices (Colla et al., 2015) ^[15].



Fig 5: Integrated Pest Management (IPM) approach combining biological, mechanical, cultural, and chemical strategies for sustainable pest control.

Integrated Pest Management (IPM) is a combination of monitoring, identification, and decision-making that is used to effectively control pests. This image depicts the concept of IPM. The management of pests in a sustainable manner is accomplished by the integration of biological, mechanical, cultural, and chemical means. While preserving crop productivity, the method places an emphasis on reducing the impact on the environment.

Decreased Potential for the Development of Resistance

Spirulina, in contrast to synthetic pesticides, exerts its effects through a variety of routes, making it difficult for pathogens to build resistance to its effects. According to El-Sheekh et al. (2014) ^[23], the inclusion of a wide variety of bioactive chemicals that target many cellular processes lowers the likelihood of resistance development, which in turn ensures that the treatment will be effective over the long term.

Safety for Humans and Other Organisms That Are Not the Target

Since it is regarded to be safe for human consumption, spirulina is commonly utilized as a nutritional supplement throughout the world.

- Non-hazardous towards both humans and animals
- A negligible effect on creatures that are helpful to the environment, such as pollinators and soil microorganisms
- Capable of supporting organic farming practices

According to Becker (2013) ^[17], due to its high level of safety, it is an excellent alternative to harmful chemical pesticides.

Economic Affordability and the Use of Renewable Resources

Spirulina is a renewable resource because it can be grown using methods that are both straightforward and environmentally friendly. Large-scale cultivation and technology improvements have the potential to bring down production costs over time, despite the fact that beginning production costs may be rather expensive. According to Habib et al. (2008) ^[18], the economic benefits of this product are significant because of its multifunctional features, which include both growth stimulation and biocontrol.

7. Limitations and Challenges of *Spirulina platensis*-Based Biocontrol

Despite the fact that *Spirulina platensis* has the potential to be a sustainable biocontrol agent, its deployment in agriculture on a broad scale is hampered by a number of constraints and problems. It is vital to address these limits in order to ensure the successful marketing of this product and its incorporation into contemporary farming systems.

The absence of field validation using a large scale

Spirulina-based biocontrol suffers from a number of problems, one of the most significant of which is the absence of large field investigations. The majority of the

research that is now available has been carried out in controlled facilities, such as laboratories or greenhouses, which do not adequately replicate challenging field circumstances.

According to Singh et al. (2011) ^[13], environmental factors such as the quality of the soil, temperature, and moisture levels, as well as interactions between microorganisms, can have a substantial impact on the efficacy of spirulina in actual agricultural settings. To prove its practical application, therefore, it is necessary to conduct field studies in multiple locations and over an extended period of time.

Variability in the Composition of Bioactive Ingredients

There are a number of factors that can influence the content of bioactive chemicals found in spirulina.

The environmental conditions of cultivation (light, temperature, and nutrients) The time for harvesting Various techniques for processing and extraction According to Becker (2013) ^[17], this diversity can end up producing findings that are inconsistent in terms of antibacterial action and the stimulation of plant development. For the purpose of ensuring that the product quality remains consistent, it is vital to standardize the cultivation and extraction processes.

A Deficit in Formulations That Are Standardized

At the moment, there is no formulation for spirulina-based biocontrol products that is universally acknowledged throughout the industry. The variations in the concentration of the extract There are variations in the application methods, which include soil, foliar, and seed treatment.

Formulations have a short shelf life and are not very stable According to Colla et al. (2015) ^[15], the presence of these characteristics makes it challenging to generate consistent results across a variety of agricultural systems and approaches to research.

High costs associated with production and processing

The production of spirulina on a commercial scale can be quite expensive, despite the fact that it is a resource that can be replenished.

- The requirement of cultivation systems that are under observation
- Inputs of either energy or nutrients
- Costs associated with processing and extraction

According to Habib et al. (2008) ^[18], the expenses associated with its production may prevent farmers from adopting it, particularly in developing nations, until more cost-effective production technologies are developed.

There is a limited understanding of the mechanisms that operate under field conditions.

Despite the fact that multiple mechanisms of action have been found through laboratory research, there is still a lack of comprehension of how these mechanisms operate when used in real-world settings.

It is difficult to fully comprehend the complex interactions that take place between spirulina, plants, the microbiota of the soil, and environmental conditions. According to Pieterse et al. (2014) ^[11], the availability of this information gap makes it difficult to maximize its application in actual agricultural systems.

Concerns Regarding Stability and Persistence

Products that are based on spirulina could experience difficulties with regard to their stability and shelf life. Over

the course of time, bioactive substances undergo degradation

A heightened awareness of environmental factors, including light and temperature

During storage, there is a decrease in effectiveness

(El-Sheekh et al., 2014) ^[23] States that the development of formulations that are stable and have a longer shelf life is vital for commercial uses.

Difficulties With Regard To Regulatory and Commercialization

Because of the following factors, the marketing of biocontrol products based on spirulina is still restricted:

- There is a lack of regulatory frameworks that are explicit for biopesticides
- Demanding a substantial amount of evidence on both safety and effectiveness
- Reduced levels of awareness among cultivators

According to Popp et al. (2013) ^[2], the regulatory approval processes can be both time-consuming and expensive, which may cause a delay in the adoption of items which are of this nature.

Limited Farmer Awareness and Adoption

There is a major lack of information among farmers regarding the advantages of goods that are based on spirulina, which is another big obstacle.

Preference for chemical insecticides that have a rapid onset of action a limited understanding of the biological options available

There is a deficiency in extended services and training.

Training programs and awareness campaigns are two of the most important things that can be done to encourage people to adopt environmentally responsible behaviors.

The Interaction with Other Inputs Provided to Agriculture

Currently, there is a lack of complete comprehension regarding the compatibility of spirulina with other agricultural inputs, including fertilizers, insecticides, and biofertilizers. Interactions that could be either antagonistic or synergistic at times

The influence on the efficiency of integrated computing systems

According to Colla et al. (2015) ^[15], additional research is required to better understand how to optimize its utilization in integrated pest management (IPM) systems in conjunction with other inputs.

8. Future Perspectives of *Spirulina platensis* in Sustainable Disease Management

As the demand for environmentally responsible and sustainable agricultural methods continues to rise, *Spirulina platensis* has emerged as a potentially fruitful contender for the development of future plant disease management systems. In spite of the fact that the current research demonstrates its promise as a biocontrol agent, there are a number of aspects that need to be investigated further in order to make its application and commercialization on a broad scale possible. The purpose of this section is to provide an overview of the most important strategies for promoting spirulina-based techniques in agriculture.

Progress in the Creation of Innovative Formulations

One of the most significant approaches that will be taken in the future is the creation of formulations of spirulina that are both stable and effective for use in agricultural applications.

- Technologies of encapsulation, such as nano- and micro-encapsulation, have the potential to enhance the stability of bioactive chemicals and allow for enhanced regulated release.
- The creation of formulations for liquids and powders that have a longer shelf life
- Improvements in both bioavailability and effectiveness in the field

According to Rai et al. (2016) ^[16], formulations that are based on nanotechnology, such as nanoparticles that are mediated by spirulina, have demonstrated better transport efficiency and have demonstrated enhanced antibacterial efficacy.

The incorporation of Integrated Pest Management (IPM) into the process

Spirulina has the potential to perform an important function in integrated pest management (IPM) systems by lowering the amount of chemical pesticides that are required.

- Combination with bacteria that are mutually advantageous, such as *Trichoderma* species and PGPR
- Integration of organic amendments and crop rotation strategies in agricultural production
- Use as a component of disease management methods that involve multiple components

According to Colla et al. (2015) ^[15], such integration has the potential to enhance the effectiveness of disease prevention while also preserving environmental sustainability.

Validation of Large-Scale Field Operations

When it comes to practical applicability, there is a requirement for comprehensive field trials that are conducted in multiple locations.

- Assessment in a variety of meteorological and soil conditions during the evaluation
- Evaluation of the effectiveness and consistency gained over the long term
- Validation over a wide variety of plant species and pathogen organisms

It will be essential to collect data at the field level in order to obtain regulatory approval and the acceptance of farmers (Singh et al., 2011) ^[13].

Research of a Molecular and Genomic Nature

Research in the future should concentrate on gaining a grasp of the molecular processes that are responsible for disease resistance that is mediated by spirulina. • Research using transcriptomics and proteomics to figure out which genes are most important for defense • An investigation into the signaling pathways in plants that are triggered by spirulina • The identification of particular bioactive chemicals that are responsible for the inhibition of pathogen cells RNA sequencing (RNA-seq) and quantitative real-time PCR (qRT-PCR) are two examples of cutting-edge techniques that have the potential to offer more in-depth understanding of the interactions between plants and microbes (Zhang et al., 2019) ^[29].

The Optimization of Production Technologies and Cultivation Methods Technologies

It is vital to create improvements in cultivation and production processes in order to make products based on spirulina economically feasible. • The development of large-scale growing systems that are efficient and cost-effective The utilization of wastewater or other low-cost sources of nutrients

Implementation of harvesting and processing methods that are optimized

According to Becker (2013) ^[17], developments in photobioreactor design and open-pond systems have the potential to increase biomass production while simultaneously lowering expenses.

Investigation of Interactions That Work Synergistically

In subsequent research, it is recommended that the synergistic benefits of spirulina be investigated in conjunction with other biological agents and organic inputs.

- Implementation in conjunction with biopesticides and biofertilizers
- Interaction with the microbiota of the soil and the dynamics of the rhizosphere
- The formation of microbial consortiums for the purpose of enhancing disease prevention and control

According to Colla et al. (2015) ^[15], the utilization of such synergistic techniques has the potential to enhance the overall effectiveness of sustainable disease control systems.

Agricultural Products That Are Climate-Resilient Applications

Solutions that are based on spirulina have the potential to contribute to climate-resilient agriculture in light of the rising climate variability.

- Improving the ability of plants to withstand abiotic stressors such as salt and drought
- Enhancing the general health of the soil in response to shifting environmental conditions
- Working to ensure the production of crops in marginal locations in a sustainable manner

In accordance with Wu et al. (2016) ^[20], the antioxidant capabilities and stress tolerance mechanisms of spirulina make it an appropriate candidate for applications of this kind.

Support for policy and commercialization of products

Policies and commercialization plans that are supportive are required in order to ensure the successful adoption of the technology.

- The creation of regulatory frameworks for products that contain biopesticides
- Support for the formation of public-private partnerships
- Programs for the education and development of farmers

According to Popp et al. (2013) ^[2], investments in research and development as well as backing from the government can help speed up the process of commercializing goods that are based on spirulina.

Prospective Paths for Future Research

Priorities for study include the following:

- Establishing procedures for extraction and application that are standardized
- Evaluation of the ecological impact over the long run
- A cost-benefit model for agricultural producers
- Creation of formulas that are tailored to certain crops

When these research gaps are addressed, it will be easier to translate the findings of the laboratory into solutions that can be implemented in agriculture.

9. Conclusion

Pathogens that are transmitted through the soil continue to be a serious obstacle for agriculture around the world because they considerably lower crop productivity and increase the risk of food insecurity. The conventional techniques of pest control that are based on synthetic pesticides, albeit being effective in the short term, have given rise to significant concerns over the environmental sustainability, the emergence of pathogen strains that are resistant to the pesticides, and the harmful effects on organisms that are not the intended targets (Aktar et al., 2009; Popp et al., 2013) [2, 1]. As a result, there is an immediate demand for alternatives that are both sustainable and kind to the environment for the management of diseases.

In short, *Spirulina platensis* (syn. *Arthrospira platensis*) has emerged as a viable biological resource due to its abundant composition of bioactive chemicals, which includes phenolics, polysaccharides, fatty acids, and pigments. This has led to the discovery of this organism. These chemicals are responsible for the powerful antibacterial, antioxidant, and growth-promoting characteristics that it possesses. In this review, it is highlighted that spirulina demonstrates a multifaceted mode of action, which includes the direct inhibition of pathogens, the suppression of fungal and nematode activity, the induction of plant defense mechanisms, and the improvement of rhizosphere microbial balance (El-Sheekh et al., 2014; Metekia et al., 2023) [24, 23]. *Spirulina* has been shown to be useful in minimizing the occurrence of diseases and boosting plant growth, as demonstrated by experimental evidence derived from experiments conducted in vitro and in greenhouses. For the time being, however, large-scale validation is still required to establish its consistency and reliability across a variety of agroecological contexts (Singh et al., 2011) [13]. Limited field investigations provide additional support for its potential under natural conditions.

Even if it has a lot of benefits, there are still a few problems that need to be solved. These problems include the unpredictable nature of the bioactive composition, the absence of standardized formulations, the high production costs, and the limited knowledge among farmers. To ensure the effective acceptance and commercialization of this technology, it will be necessary to address these restrictions through the implementation of advanced research, technological advances, and regulatory assistance.

The creation of formulations that are both stable and effective, the incorporation of these formulations into integrated pest management (IPM) systems, and the conduct of in-depth molecular studies to get a deeper understanding of the mechanisms of action should be the primary focuses of future research. In addition, in order to promote its practical implementation in agriculture, it is important to

conduct field trials on a broad scale and conduct economic feasibility evaluations.

In conclusion, *Spirulina platensis* is an alternative to chemical pesticides that is both sustainable and environmentally acceptable. It is used for the treatment of soil-borne diseases. The fact that it possesses a wide range of applications and has the potential to be incorporated into contemporary agricultural systems makes it a very useful instrument for attaining long-term agricultural sustainability and protecting the environment.

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