Microbiology Research Journal International

Volume 34, Issue 7, Page 93-112, 2024; Article no.MRJI.119338
ISSN: 2456-7043, NLM ID: 101726596
(Past name: British Microbiology Research Journal, Past ISSN: 2231-0886, NLM ID: 101608140)

The Future of Farming with Advances in Biological Control Techniques for Crop Health

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/mrji/2024/v34i71461

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/119338

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Cite as: *Akanand, A. Krishnamoorthi, Pavan K. Patel, Sonal Kumar Kumar, Chirag V khambhu, Sapna, Vijay Kumar, and Hariharan Selvam. 2024. "The Future of Farming With Advances in Biological Control Techniques for Crop Health". Microbiology Research Journal International 34 (7):93-112. https://doi.org/10.9734/mrji/2024/v34i71461.*

Review Article

Received: 19/04/2024
Accepted: 24/06/2024
Published: 29/06/2024

ABSTRACT

The future of farming holds great promise with the advancement of biological control techniques aimed at enhancing crop health and sustainability. Biological control involves harnessing natural enemies of pests, such as predators, parasitoids, and pathogens, to manage pest populations in agricultural ecosystems. This approach contrasts with conventional pesticide use, offering more environmentally friendly and sustainable solutions to pest management challenges. In recent years, biological control has seen significant technological advancements that promise to revolutionize crop protection practices. One such innovation is the development and application of microbial biopesticides, which utilize naturally occurring microorganisms like bacteria, fungi, and viruses to suppress pests and diseases. These biopesticides are often specific to target pests, minimizing harm to beneficial organisms and reducing chemical residues in crops and the environment. Moreover, the integration of precision agriculture technologies and data analytics has enhanced the efficacy and deployment of biological control strategies. Farmers can now monitor pest populations in real time, making informed decisions on when and where to apply biological agents. This precision not only optimizes pest control efforts but also minimizes input costs and environmental impact. Looking ahead, the future of farming with biological control techniques lies in further refining these methods through ongoing research and innovation. Advances in genetic technologies, such as CRISPR-based gene editing, offer the potential to engineer crops with inherent resistance to pests and diseases, reducing reliance on external control measures altogether. Furthermore, the promotion of ecological approaches like habitat manipulation and conservation biological control will enhance biodiversity and ecosystem services within agricultural landscapes, fostering resilient farming systems capable of adapting to future challenges posed by climate change and evolving pest pressures.

Keywords: Biopesticides; farmers; beneficial; biological; population; harm; pest; environment.

1. INTRODUCTION

Rising yields in the twentieth century were made possible by the development of biotechnologies and novel cultivation techniques, both of which are contributing factors in the ongoing evolution of modern agriculture. Growing food production capacity while maintaining the environment is an issue that must be overcome to feed about 9 billion people by the year 2050 [1]. Several nations are working toward the goal of increasing their food production by enhancing their farming methods, notably by employing cultivars that are more productive and resistant to the most common illnesses. Protecting crops, which is mostly accomplished via the use of chemical agents, is currently in a transitional period that requires consideration of both the socio-economic and environmental components [2]. On the other hand, these cultures are frequently attacked by parasites, which farmers need to keep under control to a degree that is below the threshold of harmfulness to live and effectively operate. The continued increase in productivity and international commerce also contributes to an increase in the prevalence of certain illnesses, which in turn necessitates the use of additional pesticides, which in turn leads to an increase in environmental pollution and the accumulation of chemical residues in the ecosystem that has been treated [3].

“It is feasible to limit pollution and nuisances related to the use of synthetic chemicals through the utilization of biological controls that make use of microorganisms. This would significantly lessen the harmful impact that synthetic chemicals have on the environment. The idea of biocontrol has sparked a significant debate in the fields of technology, economics, and politics, to achieve sustainable agriculture at a reduced cost to the environment” [4-8]. “There is significant awareness of the build-up of toxic residues in the environment and the many linkages within the food chain, as evidenced by the fact that several nations have created protective strategies that have the potential to cut around fifty percent of the harmful pesticides that are used" [9]. "Promising achievements in terms of biological control have emerged, especially after the successful use of certain antagonistic biocontrol agents (BCAs), such as Pseudomonas spp., Bacillus spp., Burkholderia spp., and Trichoderma sp. against pathogens causing foliar and soil-borne diseases like Agrobacterium radiobacter var radiobacter, Erwinia spp., Fusarium spp., *Rhizoctonia solani*, *Phytophthora spp., and Pythium spp*. On the other hand, it has been shown that the effectiveness of BCAs is always lower than that of synthetic fungicides" [10]. This is because of the intricacy of the rhizosphere, as well as the requirement that BCAs be applied continuously and sequentially. With a value of 539 million US dollars in 2015, the North American area is the largest market for biopesticides, and it is anticipated that this market will reach 1.67 billion US dollars by 2022. The research on biological control through the use of microorganisms is experiencing and growing speed, although there are still very few applications in the field [11].

1.1 What is Biological Control?

"In the process of managing plant diseases, a method known as biological control is utilized. This method involves the inhibition of the pathogen or disease-causing organism by another organism. The helpful organism is referred to as the biological control agent, or BCA for short. Specialized metabolites, which are compounds that have signalling, antimicrobial, or attractant actions, are included in a more comprehensive description" [12]. These chemicals are sometimes referred to as biopesticides. On the other hand, people should steer clear of the misleading word "biopesticides" and instead use the term "bioprotectants." The traditional BCAs are natural enemies that may self-proliferate and establish themselves in the environment to reduce the number of pest populations. To reduce the number of pests and pathogens in a particular area, augmentative BCAs are natural enemies that are manufactured in large quantities and then delivered into that ecosystem regularly [13]. "These agents can be further differentiated between seasonal inoculative agents, which can reproduce and remain in the soil during the growing season, and inundative agents, which are unable to proliferate and must be reapplied often throughout the growth season" [14]. The use of biological control presents several options for the improvement of disease control, particularly in situations when traditional methods are either limited or hindered. Within the context of integrated pest control techniques, it is a significant component that contributes to the reduction of the application of chemical pesticides [15]. Rather than being a chemical in and of itself, a biological control agent (BCA) is an organism or collection of organisms. It is far more likely to have a more precise impact than the majority of commercially available agrochemicals, and it is also less likely to leave behind potentially dangerous residues in the environment. In a manner that a chemical cannot, a live organism could be able to enter the damaged plant or have an effect on the pathogen that is the objective of the treatment. When a BCA is applied, there is a significant reduction in the likelihood that microorganisms may develop resistance to a chemical pesticide [16]. This is the case in certain circumstances. Biological control is also considered by the general public to be more natural and less detrimental to the environment than chemical control. Furthermore, several kinds of biological control are also recognized for their usage in organic farming [17]. It has been suggested that a BCA could be more cost-effective than a pesticide in some circumstances. BCAS may be traced back to 1932, when Weindling published multiple studies indicating that a Trichoderma isolate could minimize damage to citrus seedlings caused by *Rhizoctonia solani* and detailing some of the probable mechanisms of action. This is where the history and genesis of BCAS can be found [18]. Today, Trichoderma species are arguably the organisms that are employed the most frequently as BCAs to control plant diseases all over the world. Not only was biological control considered a technique in the 1980s, but it was also considered a philosophy to reduce crop loss that was caused by plant diseases [19]. Pioneering researchers such as Claude Alabouvette, Dijon, France, David Weller, Linda Thomashaw, and R. J. Cook have made significant contributions to our understanding of the biology of disease or pathogen-suppressive soils. These efforts have been crucial in accomplishing this goal. Several new crop protection products that are derived from microorganisms have come into existence. These products include BCA products that are derived from A*. radiobacter* and *P. gigantean* [20].

1.2 Mechanisms Involved in Biocontrol

Since its inception in Egypt four thousand years ago, the notion of biological control, also known as BCAs, has been a promising method to the treatment of plant diseases. The investigation into the use of BCAs for the management of plant diseases was prompted by the finding that certain soil-borne illnesses were reduced by the presence of antagonistic microbes, such as Bacillus subtilis and Ampelomyces quisqualis Ces [21]. Since then, research in biological control has undergone a revolution, leading to the development of a multitude of BCAs. These BCAs include the exploitation of beneficial microbes, plant inducers, microbial metabolites, and plant extracts in crop diversification [22].

- “Certain microorganisms are hyperparasites, meaning that they create antibiosis to kill pathogens directly, or they depend on infections for their energy source or their living surroundings” [23]. “The release of chemicals or antimicrobials by other organisms may put them in competition with one another for niches and resources. These attributes are possessed by some fungus, mycoviruses, and bacteriophages, which have the potential to be BCAs that are enhanced against plant diseases and deployed in fields once or several times, depending on the biological characteristics and habitats of the fungi, mycoviruses, and bacteriophages” [24]. “Additionally, secondary metabolites and chemicals that are generated by microbial or non-microbial species have the potential to be utilized as pathogen inhibitors to control plant diseases. Plants can protect themselves by creating substances that either kill diseases or stimulate the growth of bacteria that are helpful to the plant” [25]. It is possible to extract these substances from plants and then employ them in conjunction with antimicrobials or metabolism provided by helpful microorganisms like BCAs.

- “The interaction of some beneficial microorganisms with plants can either establish host resistance or trigger host defense responses without the germs coming into direct contact with pathogens” [26]. “These agents consist of natural products and chemical compounds that are created by a variety of sources. Some examples of these agents are plant extracts, microbial metabolites, synthetic chemicals, and gene products” [27]. “Numerous secondary metabolites that are involved in signal transduction and catalytic activities, as well as chemicals like salicylic acid, acetylsalicylic acid, and nitric oxide, possess features that increase host plant immunity and enhance host resistance” [28]. “These chemicals are responsible for the systemic acquired resistance that is found in host plants after they have been infected by pathogens. Rhizobacteria, along with a wide variety of other non-pathogenic microorganisms, are capable of producing these antimicrobial compounds” [29].

- On the other hand, the exploitation and usage of active compounds for BCAs for commercial application is often expensive and less efficient. This is largely due to the temporal lag that occurs when plant resistance is induced. The regulation of the ecosystem to safeguard and encourage the growth of natural adversaries or competitors of pathogens [30].

- Plant diseases are frequently the consequence of an ecosystem that is out of balance, and the efficacy of biological management is contingent on the existence of a healthy ecosystem that is populated with predators, competitors, promoters, and other various species. When it comes to the maintenance of a healthy ecosystem for the growth and development of immunity in plants, the microbiome's positive interaction with other organisms in soil communities is of utmost importance [31]. Through a variety of processes, crop diversity has the potential to reduce plant diseases. These mechanisms include inoculum dilution, the construction of physical barriers that restrict pathogen transmission, the amelioration of pathogen pathogenicity, fungicide resistance, and evolution. Additionally, crop variety promotes soil fertility and microbial diversity, which in turn increases the availability of nutrients for demanding crop growth and the complexity of microorganisms to compete with diseases [32].

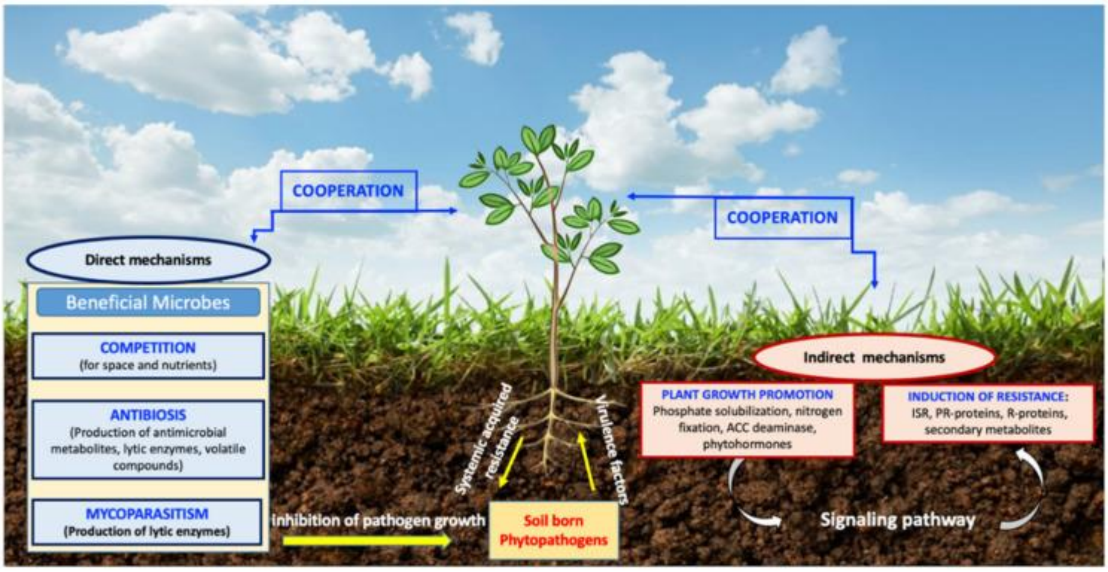

Fig. 1. Biological control process

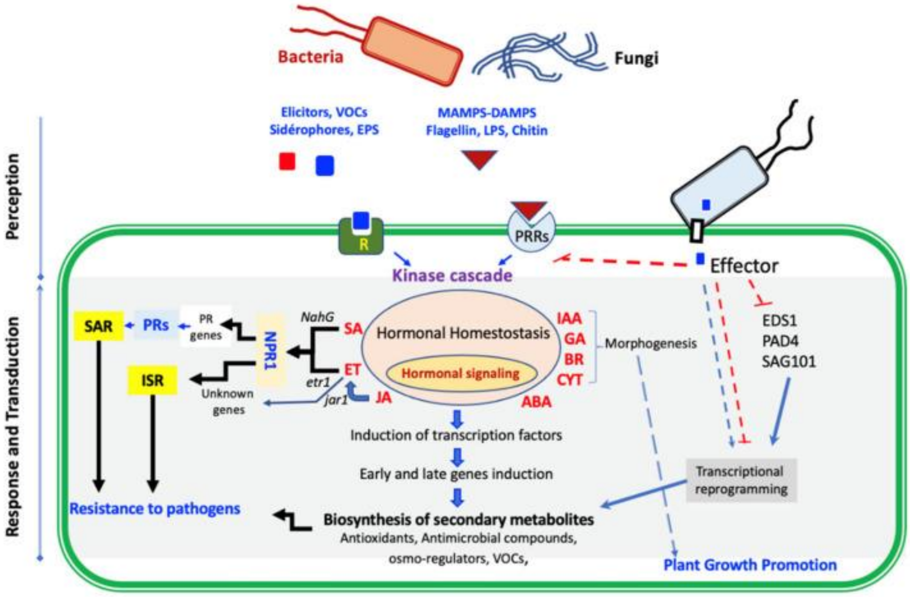

Fig. 2. Mechanisms involved in biocontrol

2. MICROBIAL CONTROL IN AGRICULTURE

2.1 Microbial Control

The administration of plant pathogens through biocontrol involves the implementation of a variety of techniques. Microbial biocontrol is a technique that entails the rhizosphere, the soil region encircling roots, which is constituted of microbes that are capable of suppressing plant pathogens. This assists in the natural defence of plants against a variety of organisms by synthesizing metabolites that are antagonistic to the pathogens or indirectly by suppressing pathogen growth and enhancing the host's defence mechanisms [33].

Plant growth-promoting rhizobacteria (PGPR) that are present in the rhizosphere also contribute to biocontrol by reducing the prevalence of plant diseases and promoting plant growth. PGPR also promote antibiosis, competition, the production of metabolites that induce systemic acquired resistance (SAR) and induction of systemic resistance (ISR), parasitism, and the production of hydrolytic enzymes such as cellulase, glucanase, chitinase, and protease that break down the cell wall, as well as antibiotics such as oomycin A, 2,4-diacetyl phloroglucinol (DAPG), and pyoluteorin [34].

Rhizobia are symbiotic microorganisms that are present on the roots of leguminous plants and are crucial for the biocontrol and nitrogen fixation processes. They inhibit the growth of pathogenic fungi from genera such as Fusarium, Rhizoctonia, Sclerotium, and Macrophomina by secreting antibiotics, mycolytic enzymes, siderophores, and hydrocyanic acid (HCN). This process promotes plant growth. By increasing the expression of defence-related genes and initiating systemic resistance, they improve plant immunity [35].

Endophytes are also utilized as biocontrol agents in the management of plant diseases. These organisms can exist in various components of a plant, including roots, leaves, and branches, without causing any symptoms. Potential antagonistic variants of endophytes can be screened for biocontrol capability, as all strains do not exhibit similar activity. To fully leverage their potential as future disease and pest management agents, it is imperative to conduct comprehensive research on their biocontrol activity [36].

2.2 Fungal Biocontrol

Fungi also possess biocontrol capabilities, which they employ to combat parasites such as nematodes and microbial pathogens that infect different portions of the plant. Through processes such as antibiosis, competition for resources with pathogens, mycoparasitism, conferring ISR to the host plant, and mycovirus-mediated cross-protection (MMCP), they protect against diseases [37]. Trichoderma species, ectomycorrhizas, arbuscular mycorrhizas (AMF), yeasts, and endophytes are among the most well-known fungal biocontrol agents. By introducing advantageous fungal genes into the genomes of host plants and interrupting or overexpressing these genes, it is feasible to enhance biocontrol capabilities through the application of enhanced biotechnological and genetic advancements [38]. A review conducted by Thambugala et al. offers a comprehensive list of fungal biological control agents that are employed to combat fungal plant pathogens by contemporary taxonomic concepts. Additionally, the review clarifies the phylogenetic relationships of these agents. Trichoderma is recognized as the genus with the most potential for biocontrol, with 25 species that are employed as biocontrol agents against a variety of plant fungal diseases [39].

Trichoderma species are filamentous fungi that are borne in the soil and have a variety of health benefits for plants. The pathogen control mechanism they employ is intricate, involving the colonization of the soil and root of the host, the habitation of physical space, the production of cell wall-degrading enzymes, antimicrobial metabolites to eliminate pathogens, the induction of plant defense mechanisms, the promotion of plant development, and the enhancement of plant tolerance to biotic and abiotic stressors. Additionally, they evade the multiplication of phytopathogens [40].

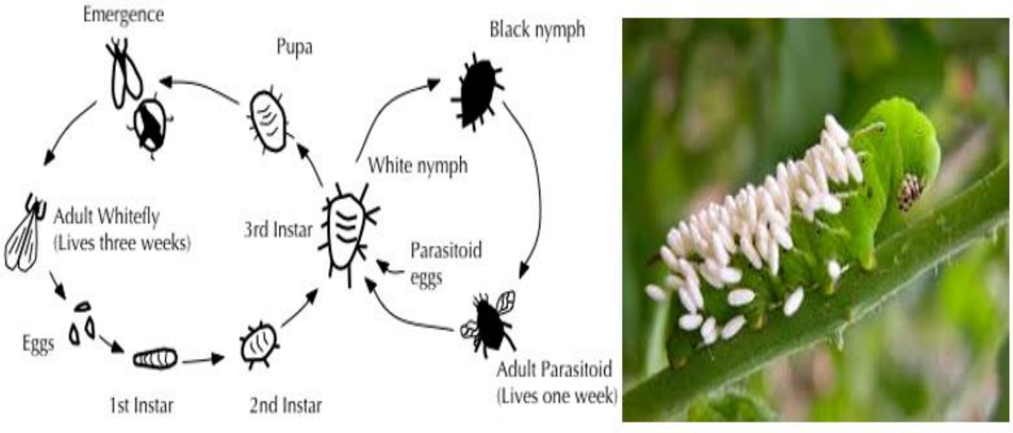

Fig. 3. Microbial control in agriculture

2.3 Viral Biocontrol

The effects of plant viruses, including *Sclerotinia sclerotiorum* hypovirulence-associated DNA virus 1 (SsHADV-1), on a variety of crops have been the subject of research. The following are examples of common beneficial plant viruses: acute viruses such as Brome mosaic virus, Cucumber mosaic virus, Tobacco rattle virus, and Tobacco mosaic virus (family Virgaviridae), which provide tolerance to drought and freezing temperatures in a variety of crops; and persistent viruses like White clover cryptic virus (family Partitiviridae), which can suppress nodulation in legumes when a sufficient nitrogen supply is provided [41,42].

The control of plant viruses is achieved through host resistance, mild strain cross-protection, or biocontrols of their insect vectors, such as parasitoids of mealybugs that vector GLRaV-3. Race-specific resistance is typically induced by host R genes in response to the Avr genes of pathogens in the event of host resistance [43]. An HR response that is triggered by the R gene is essential during plant–virus interactions that take place in a single cell. This response is responsible for the death of infected cells and the restriction of viral invasion [44]. This phenomenon is linked to a variety of molecular events, including the activation and expression of salicylic (SA), jasmonic acid (JA), mitogen-activated protein kinase signaling, calcium ion influx, callose deposition at the plasmodesmata, membrane permeability modification, pathogenesis-related (PR) protein expression, and the immediate accumulation of reactive oxygen species and nitric oxide [45].

3. OTHERS METHODS

Studies have demonstrated that arbuscular mycorrhizal fungi (AMF) can decrease the frequency of nematode attacks and fungal diseases on host plants by 30 to 42% and 44 to 57%, respectively. AMF provides protection against a variety of fungal pathogens from the following genera: Colletotrichum, Alternaria, Erysiphe, Gaeumannomyces, Macrophomina, Botrytis, Rhizoctonia, Fusarium, Cylindrocladium, Sclerotium, and Verticillium. Nevertheless, they provide inadequate defense against a substantial number of viral and bacterial pathogens [46].

The presence of mycorrhizal fungi appears to exacerbate the damage caused by viral infections in the case of viral pathogens, as evidenced by the presence of Tomato spotted wilt virus (TSWV), Potato virus Y, Citrus tristeza virus, Citrus leaf rugose virus, and Tobacco mosaic virus. AMF's impact on viral pathogens is not entirely apparent; however, it appears to be primarily supportive, leading to an increase in disease severity [47]. Furthermore, AMF exhibits diminished colonization and spore formation when the host plant is infected with a viral pathogen such as the yellow mosaic virus [48]. Due to their efficacy against a variety of plant pathogens, biocontrol yeasts, including Aureobasidium pullulans, Cryptococcus albidus, Candida oleophila, Saccharomyces cerevisiae, and Metschnikowia fructicola, are currently employed as biocontrol agents [49]. They are unicellular fungi that are capable of growing in a wide range of environments, have minimal cultural requirements, and pose few biosafety concerns. Phage-based competition, enzyme secretion, toxin production, volatiles, mycoparasitism, and the induction of resistance activity are the mechanisms by which they exert their biocontrol activity [50]. Ferraz et al. have comprehensively documented the successful applications of yeasts in combating filamentous fungi-induced produce deterioration. An exhaustive compendium of commercialized fungal biocontrol agents for plant fungal diseases and their specifications has been compiled by Thambugala et al [51]. Candida oleophila, Aureobasidium pullulans, Metschnikowia fructicola, and numerous other yeast species have been registered as biocontrol agents and have been proposed as potential commercial biocontrol agents [52]. The potential antagonists against phytopathogenic fungi of the genera Penicillium and Aspergillus, as well as the species Botrytis cinerea, on table grapes, wine grapes, and raisins are suggested by Di Canito et al. Saccharomyces and non-Saccharomyces yeasts. Several non-conventional species remain mainly unexplored in both fundamental research and for their potential commercialization [53]. This group is a vast, untapped reservoir of yeasts that have the potential to drive biotechnological innovations. It is composed of a selection of species and strains that possess novel metabolic traits, including the secretion of proteins, adhesiveness, and antimicrobial properties, which are necessary for yeasts to demonstrate their usefulness as biocontrol agents. A new strategic frontier for the preservation of the post-harvest quality of table and wine grapes is the application of yeasts in the prevention of infections [54].

For an extended period, phages have been employed as biocontrol agents against bacterial pathogens. Mallmann and Hemstreet isolated Xanthomonas campestris pv. campestris from plant tissues affected by the cabbage-rot disease in 1924, which was the first study to demonstrate their biocontrol capabilities. Recent investigations into the application of phage biocontrol have concentrated on enhancing their durability in field environments [55]. Peptidoglycan hydrolases, lysins from phages Atu_ph02 and Atu_ph03, and other lysins from CMP1 and CN77 phages have demonstrated lytic capacity against Clavibacter michiganensis subsp. michiganensis, resulting in bacterial wilt and canker of tomato [56].

The application of phages and phage lysins in plant disease management is a progressive step, with the current emphasis on the development of improved delivery mechanisms and the assurance of an extended shelf life for the phage and its enzymes on the host plant [57].

Natural compounds that are bioactive, including those in the phenolic, terpenoid, and alkaloid categories, can be employed to promote plant growth and control disease. Garlic, allicin, terpenes, chitosan, naringin, and carrageenans are among the bioactive molecules that have been identified for use as biopesticides in organic cultivation [58]. Under field conditions, allicin, which is derived from garlic, demonstrates antibacterial and antifungal properties, thereby preventing the proliferation of a variety of bacteria and fungi. Naringin, which is present in grapefruit seeds and pith, is effective against fusariosis, alternariosis, and gray mold infections in soybeans, ornamental plants, and vegetables such as potatoes. Tea tree oil, which is composed of terpenes such as gamma-terpinene, terpinen-4-ol, and 1,8-cineole, possesses potent antimicrobial properties that are effective against a diverse array of bacteria and fungi. It is particularly effective against Bremia lactucae and downy mildew, which cause damage to lettuce [59].

Chitin, the second most ubiquitous polysaccharide in nature, exhibits bioactivity against bacterial, viral, and fungal organisms. It has been identified as a fungal microbe-associated molecular pattern (MAMP) molecule that activates immune responses in the host plant and has a potent antifungal effect on soil-borne pathogenic fungi that infect soybeans. The immune response is initiated by bioactive compounds, which bind to membrane receptors on plants and produce a signal [60].

Algal and cyanobacteria extracts are abundant sources of bioactive elicitors that possess antibacterial, antiviral, and antifungal properties. Typically, these extracts are employed in agriculture to enhance the vitality of plants and increase productivity. Studies conducted on tomato seedlings that were infected with *Macrophomina phaseolina* demonstrated that the administration of Kappaphycus alvarezii resulted in an improvement. The utilization of extracts from Cystoseira myriophylloides, Laminaria digitata, and Fucus spiralis against Verticillium dahliae wilt was also demonstrated to enhance the activity of polyphenol oxidase and peroxidase enzymes, which are crucial for plant defence in tomatoes [61].

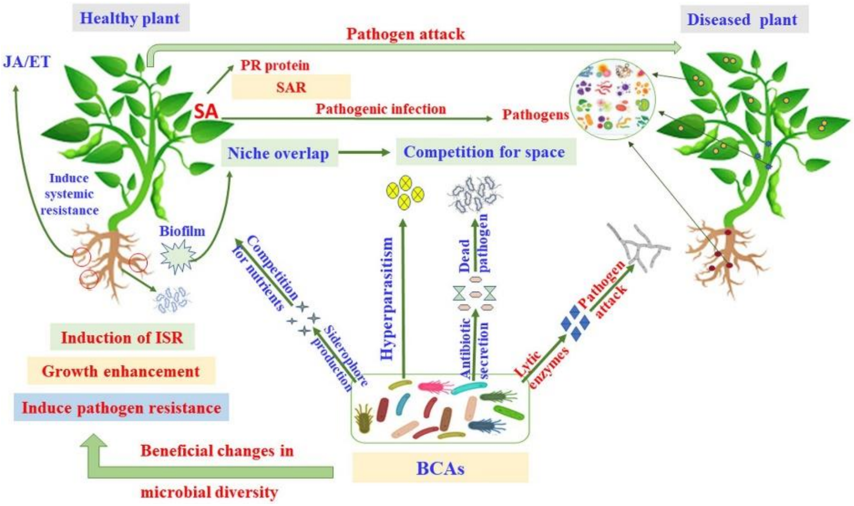

Fig. 4. Viral biocontrol

Table 1. Biological control methods commonly used in vegetable crops

Biological Control Methods	Description	Target Pests	Examples
Predatory Insects	Release of beneficial insects that prey on pest species, controlling their populations through predation.	Aphids, thrips, mites, caterpillars	Ladybugs (ladybird beetles), lacewings, predatory mites
Parasitoids	Insects that parasitize and eventually kill their hosts.	Caterpillars, moth larvae	Trichogramma wasps, Braconid wasps
Microbial Biopesticides	Use of naturally occurring microorganisms to target and control specific pests and diseases.	Caterpillars, beetles, fungal diseases	Bacillus thuringiensis (Bt), Beauveria bassiana (fungus)
Entomopathogenic Nematodes	Microscopic roundworms that infect and kill insect pests in the soil.	Root maggots, caterpillars, beetle larvae	Steinernema feltiae, Heterorhabditis bacteriophora
Trap Crops and Companion Planting	Planting certain crops or plants to attract pests away from main crops or using companion plants to repel pests or attract beneficial insects.	Aphids, nematodes, whiteflies	Mustard greens (trap crop), marigolds (companion plant)
Augmentation and Conservation of Natural Enemies	Releasing beneficial insects into crops or preserving their habitats to enhance biological pest control.	Aphids, spider mites, thrips	Release of predatory insects, creation of habitat refuges

Table 2. Biological control methods used in different fruits, along with examples and target pests

Fruit Crop	Biological Control Methods	Description	Target Pests	Examples
Apples	Predatory Insects	Beneficial insects released to prey on pests like aphids, mites, and leafhoppers, reducing populations through predation.	Aphids, mites, leafhoppers	Ladybugs (Coccinellidae), lacewings, predatory mites
	Parasitoids	Insects that parasitize pest larvae such as codling moth and leafrollers, controlling populations by killing host pests.	Codling moth, leafrollers	Trichogramma wasps, Braconid wasps
	Microbial Biopesticides	Application of biopesticides containing naturally occurring microbes to manage diseases like apple scab and powdery mildew.	Apple scab, powdery mildew	Bacillus thuringiensis (Bt), Metarhizium anisopliae (fungus)
Citrus	Entomopathogenic Nematodes	Soil application of nematodes to target pests such as citrus root weevils and fruit borers, reducing larval populations in the soil.	Citrus root weevils, fruit borers	Steinernema carpocapsae, Heterorhabditis bacteriophora

Fruit Crop	Biological Control Methods	Description	Target Pests	Examples
	Trap Crops and Companion Planting	Planting trap crops to divert pests away from citrus trees, or using companion plants like marigolds to repel pests and attract beneficial insects.	Citrus leafhoppers, aphids	Marigolds (companion plant), mustard greens (trap crop)
Grapes	Augmentation of Natural Enemies	Release of predatory insects such as ladybugs and predatory mites to control pests like grape phylloxera and leafhoppers.	Grape phylloxera, leafhoppers	Ladybugs (Coccinellidae), predatory mites
	Biological Control via Fungi	Utilization of fungi to combat fungal diseases such as powdery mildew and downy mildew, promoting healthier grapevine growth.	Powdery mildew, downy mildew	Trichoderma spp., Ampelomyces quisqualis (fungus)
Strawberries	Conservation of Natural Enemies	Preservation of habitats and plant diversity to support populations of beneficial insects that prey on pests like strawberry aphids and spider mites.	Strawberry aphids, spider mites	Conservation of native predators, habitat management practices
	Biopesticides	Application of bio-based pesticides to control pests and diseases, reducing reliance on synthetic chemicals.	Two-spotted spider mites, strawberry crown rot	Beauveria bassiana (fungus), Bacillus thuringiensis (Bt)

Table 3. Biological control methods used in different agronomic crops, along with examples and target pests

Crop Type	Biological Control Method	Description	Target Pests	Examples
Corn (Maize)	Predatory Insects	Release of beneficial insects like ladybugs and lacewings to prey on pests such as corn earworms and aphids, reducing populations naturally.	Corn earworms, aphids	Ladybugs (Coccinellidae), lacewings
	Microbial Biopesticides	Application of microbial agents like Bacillus thuringiensis (Bt) to target pests such as corn borers and armyworms, reducing larval populations.	Corn borers, armyworms	Bacillus thuringiensis (Bt), Metarhizium anisopliae (fungus)
Wheat	Parasitoids	Use of parasitic wasps (e.g., Trichogramma species) to parasitize eggs of wheat pests like Hessian flies and aphids, controlling their populations.	Hessian flies, aphids	Trichogramma wasps, Braconid wasps
	Entomopathogenic Nematodes	Soil application of nematodes to target soil-dwelling pests such as wheat wireworms and root aphids, reducing larval populations effectively.	Wheat wireworms, root aphids	Steinernema carpocapsae, Heterorhabditis bacteriophora
Rice	Augmentation of Natural	Release of predatory insects like dragonflies and water	Rice leaf folders,	Dragonflies, water bugs

Crop Type	**Biological Control Method**	**Description**	**Target Pests**	**Examples**
	Enemies	bugs to control pests such as rice leaf folder larvae and stem borers in rice paddies.	stem borers	
	Biopesticides	Use of bio-based pesticides to manage pests and diseases in rice fields, promoting sustainable pest management practices.	Rice blast, brown planthoppers	Beauveria bassiana (fungus), Pseudomonas fluorescens
Soybean	Conservation Biological Control	Preservation of natural habitats and plant diversity to support populations of beneficial insects that prey on soybean pests like aphids and stink bugs.	Soybean aphids, stink bugs	Conservation of native predators, habitat management practices
	Genetic Resistance	Development of genetically resistant soybean varieties against specific pests and diseases, reducing the need for external pest control measures.	Soybean cyst nematode, soybean aphids	Resistant soybean cultivars engineered through breeding programs
Cotton	Microbial Biocontrol Agents	Application of microbial agents like Bacillus thuringiensis (Bt) to manage pests such as cotton bollworms and aphids, reducing larval and adult populations.	Cotton bollworms, aphids	Bacillus thuringiensis (Bt), Beauveria bassiana (fungus)
	Trap Crops and Companion Planting	Planting trap crops like sunflowers or using companion plants to attract beneficial insects and repel pests such as whiteflies and thrips.	Cotton whiteflies, thrips	Sunflowers (trap crop), marigolds (companion

Cyanobacteria have been employed to combat plant pathogens at both the soil and leaf levels. Seedling endurance, root and shoot dry weight, and plant length were significantly improved by the use of Nostoc entophytum and Nostoc muscorum in the soil to combat Rhizoctonia solani. In tomato, the application of Nostoc linckia to the soil against Fusarium oxysporum f. sp. Lycopersici resulted in a reduction in wilt, while Nostoc commune was observed to ameliorate the condition of similarly infected seedlings [62]. Cyanobacteria, similar to phytoplankton, are capable of producing high levels of polysaccharides in response to a variety of plant pathogens. However, their potential as biocontrol agents is restricted by a lack of relevant data [63,64].

4. PLANTS' INTERACTION IN BIOLOGICAL CONTROL

During their lifespan, plants and diseases interact with a wide variety of species, which can have a substantial impact on the health of the plant. Having an appreciation for the many ways in which organisms interact is essential to comprehend the systems that are responsible for biological regulation [65]. In his proposal from 1953, Odum suggested that the results for each population should be used to determine interactions between two populations. Mutualism, protocooperation, commensalism, neutralism, competition, amensalism, parasitism, and predation are the different sorts of relationships that can occur [66]. When seen from the point of view of the plant, biological control may be regarded as a predominantly beneficial result, as it is the outcome of a wide range of interactions, both specific and non-specific. The relationship between two or more species in which both of the species benefit from the relationship is known as mutualism [67]. A kind of mutualism known as protocooperation occurs when the organisms involved do not rely only on one another for their existence. The term "commensalism" refers to a symbiotic relationship between two living creatures, in which one organism benefits while the other organism both benefits and is not damaged by the relationship. When the population density of one species has absolutely no influence whatsoever on the other species, this type of biological interaction is referred to as neutralistic ecological interaction [68].

There is a decline in growth, activity, and/or fertility among the organisms that interact with one another as a result of competition both within and across species. Non-pathogens can compete with pathogens for nutrients within and around the host plant, which result in the process of biocontrol [69]. There are also direct interactions that affect our knowledge of biological regulation. These interactions benefit one species at the expense of another population. Parasitism is a type of symbiosis that occurs when two organisms that are not linked to each other phylogenetically persist for an extended length of time [70]. Biocontrol can be achieved by the actions of a wide variety of hyperparasites, such as agents that parasitize plant diseases. The term "predation" refers to the act of one organism seeking and killing another organism to consume and sustain itself. Although the term "predator" is most commonly used to describe animals that eat at higher trophic levels in the macroscopic world, it has also been used to describe the behaviours of microorganisms, such as protists, and mesofauna, such as fungal feeding nematodes and microarthropods, who obtain their nutrition by consuming pathogen biomass [71-73].

The environmental context in which each of these sorts of interactions takes place can have a significant impact on the degree to which biological control can ultimately come from each of these interactions [74]. In most cases, significant biological control is achieved by controlling the mutualisms that exist between microorganisms and the plants that they inhabit, or by regulating the antagonistic relationships that exist between microbes and different diseases [75].

5. CHALLENGES

Biological control techniques for crop health, while offering numerous advantages, also face several challenges that can impact their effectiveness and adoption. Here are some key challenges:

1. **Complexity and Variability**: Biological control methods often involve complex ecological interactions between pests, natural enemies, and environmental conditions. Variability in natural enemy effectiveness, pest populations, and climatic factors can influence the reliability and consistency of biological control outcomes [76].
2. **Slow Action and Response**: Unlike chemical pesticides, which often provide immediate and predictable results,

biological control agents may take time to establish and achieve effective pest suppression. This slower action can be a limitation in situations requiring rapid pest management responses, such as during pest outbreaks or in high-value crops [77].

3. **Specificity and Narrow Target Range**: Many biological control agents are highly specific to certain pest species or life stages. This specificity can be advantageous for preserving beneficial organisms but limits their utility in managing complex pest communities or sudden shifts in pest dynamics [78].
4. **Risk of Disruption and Non-Target Effects**: Introducing non-native biological control agents or species into new environments can pose risks of unintended consequences. These include potential impacts on non-target species, unintended disruption of native ecosystems, or establishment of invasive species [79].
5. **Cost and Investment**: Initial costs associated with biological control can be significant, involving research, development, and implementation of suitable strategies and agents. Additionally, ongoing monitoring and management may require continued investment compared to one-time applications of chemical pesticides [80].
6. **Knowledge and Training**: Effective implementation of biological control methods often requires specialized knowledge and training. Farmers and practitioners need to understand ecological interactions, pest and natural enemy biology, and optimal application techniques to maximize success [81].
7. **Integration with Other Pest Management Strategies**: Biological control methods are most effective when integrated into broader integrated pest management (IPM) strategies that combine multiple approaches. However, integrating biological control with chemical pesticides or cultural practices requires careful planning to avoid conflicts and optimize outcomes [82].
8. **Resistance and Adaptation**: Pests can develop resistance to biological control agents over time, similar to resistance observed with chemical pesticides. Continuous monitoring and adaptation of strategies are necessary to address evolving pest pressures and maintain effective pest management [83].
9. **Regulatory and Policy Frameworks**: Regulatory approval processes for biological control agents can be lengthy and stringent, varying between countries and regions. Compliance with regulatory requirements for safety, efficacy, and environmental impact is essential but can pose barriers to adoption [84].
10. **Public Perception and Acceptance**: Public perception of biological control methods, particularly those involving genetically modified organisms (GMOs) or non-native species, may influence their acceptance and adoption. Addressing concerns about safety, environmental impact, and ethical considerations is crucial for broader societal acceptance [85].

5.1 Advantages

Biological control techniques offer several advantages for maintaining crop health and promoting sustainable agriculture. Here are some key advantages:

1. **Environmentally Friendly**: Biological control methods rely on natural predators, parasites, pathogens, or competitors to manage pest populations. Unlike chemical pesticides, they do not leave harmful residues in soil, water, or on crops, reducing environmental pollution and promoting ecosystem health [86].
2. **Target-Specific Control**: Biological control agents often target specific pests while sparing beneficial organisms. This precision helps maintain biodiversity and ecological balance in agricultural ecosystems, minimizing disruption to natural pest control mechanisms [87].
3. **Reduced Pesticide Dependency**: By integrating biological control into integrated pest management (IPM) strategies, farmers can reduce reliance on synthetic pesticides. This approach mitigates the development of pesticide resistance in pest populations and reduces the risk of secondary pest outbreaks [88].
4. **Long-Term Effectiveness**: Biological control can provide sustainable, long-term pest management solutions. Once established, beneficial organisms can persist and continue to suppress pest populations over multiple growing seasons without continuous inputs [89].

5. **Compatibility with Organic Farming**: Many biological control methods are compliant with organic farming standards. They support organic certification by aligning with principles of natural and sustainable agriculture practices [90].
6. **Cost-Effectiveness**: While initial setup costs may be comparable to chemical pest control, biological control can lead to cost savings over time. Reduced pesticide applications, lower labor costs for application, and decreased need for pest management inputs contribute to overall economic efficiency [91].
7. **Enhanced Food Safety**: Biological control methods contribute to producing safer food with reduced pesticide residues. Consumers increasingly prefer produce grown with fewer chemical inputs, aligning with food safety and quality standards.
8. **Resilience to Climate Change**: Biological control enhances agricultural resilience to climate change by fostering diverse, healthy ecosystems. Natural enemies and beneficial organisms may adapt more readily to changing environmental conditions, helping crops withstand stresses such as temperature fluctuations or altered precipitation patterns [92].
9. **Community and Public Health Benefits**: By minimizing pesticide exposure to farm workers, nearby communities, and consumers, biological control methods promote better public health outcomes. They contribute to safer working environments and reduce health risks associated with pesticide exposure [93].
10. **Innovation and Research Opportunities**: Ongoing research and innovation in biological control techniques continually expand the range of effective agents and strategies available to farmers. Advances in biotechnology, genetics, and ecological sciences further enhance the efficacy and applicability of biological control in modern agriculture [94].

6. CONCLUSION

In conclusion, while biological control techniques offer promising solutions for sustainable crop health management, their successful implementation requires careful consideration of various factors. These techniques, which leverage natural predators, parasites, pathogens, and ecological processes, provide environmentally friendly alternatives to chemical pesticides. They contribute to reducing pesticide residues in food, preserving biodiversity, and promoting ecosystem resilience. However, challenges such as complexity in ecological interactions, variability in effectiveness, and the risk of unintended ecological impacts underscore the need for integrated pest management (IPM) approaches. Combining biological control with cultural practices, genetic resistance, and judicious use of chemical interventions can enhance overall pest management efficacy while minimizing risks. Moreover, ongoing research, innovation, and education are essential to address knowledge gaps, improve biological control agent specificity and efficacy, and foster sustainable agricultural practices globally. Regulatory frameworks must support safe and responsible use of biological control agents, ensuring they meet safety and efficacy standards while facilitating adoption by farmers. Looking ahead, the continued development and adoption of biological control methods hold great potential for advancing sustainable agriculture and food security. By embracing these techniques alongside other IPM strategies, stakeholders can work towards resilient farming systems that support both environmental conservation and economic viability in agriculture.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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