Biological Control: A Potential Tool for Pest Management under Changing Climatic Conditions

M. Siva[1], K. Saravanakumari[1*], M. Nivedha[1], P.S. Saranya[1], D.S. Srimahesvari[1], P.Yazhini[1], E.Santhoshinii[2], D. Shanmugapriya[3]

[1]*Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu - 641 003, India*

[2]*Department of Plant Pathology, University of Agricultural Sciences, Dharwad, Karnataka - 580 005, India*

[3]*Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu - 641 003, India*

Abstract

The impact on food availability is mostly influenced by changing climatic circumstances such as increased CO2 levels, shifting rainfall patterns, and temperature fluctuations. These elements primarily cause severe weather events such as floods, storms, droughts, and wildfires, all of which influence food availability. In recent years, unusually diverse abrupt weather conditions and catastrophic events have aided the quick introduction and reemergence of invasive plant pest species, as well as their increased pesticide resistance, posing a threat to food security. As pests and pathogens move into new areas, they can encounter new hosts and ecosystems, leading to novel interactions and potentially severe impacts on agriculture and natural ecosystems. To control them enormous amounts of pesticides are used by farmers. The alarming rise in pesticide usage will compound the problem by polluting land, air, and water, as well as causing the establishment of pesticide-resistant insect populations. As a result, a shift toward environmentally friendly and cost-effective practices is necessary, which should apply to both proactive and reactive solutions. Microbial biological control agents (MBCAs) are used on crops to prevent plant diseases by both direct and indirect processes such as antibiosis, parasitism, and reactive oxygen species formation, cell wall dissolving enzymes, competition, and induced resistance in crop plants. Understanding the nature of biocontrol agents allows for improved pest management in today's changeable climatic circumstances. Furthermore, these procedures will aid in the development of appropriate management strategies to mitigate the detrimental effects of pests like insects and pathogens on food security and biodiversity.

Introduction

Global climate change is a change in the long-term weather patterns around the regions of world. It poses a significant threat to global food security and nutrition, which impacts agricultural productivity, availability

***Corresponding author's e-mail**: saraerbium@gmail.com

Enhancing Crop Resilience: Advances in Climate Smart Crop Production Technologies. Anjani Kumar, Rameswar Prasad Sah, Basana Gowda et al. (Eds). © 2024, BIOTICA.

and accessibility to nutritious food. Farmers play a crucial role in food production, as temperature rises and weather patterns become more erratic, it makes the ability of the farmers to do suitable cropping pattern is highly challenging, which leads to potential disruptions in food production system. The factors such as temperature and precipitation patterns can alter the taste, texture and quality of agricultural products such as apples and grapes, which affects the consumer preference and market quality. The beneficial insects such as pollinators, predators and pollinators also prone to climate change and potentially disrupting the ecosystem which is necessary for food production.

Climate change will also have a direct effect on the composition, distribution and life cycle of the weeds and pests of pastures, crops, orchards and forests. The interplay between climate change and food security is very complex and multifaceted problem that requires urgent attention and coordination to act at local, national and global levels. Biological control is currently receiving much attention in disease management programs. The overuse of chemicals has created an unprecedented environmental crisis. Though biological control cannot replace chemicals, it can certainly minimize the development of resistance. Certainly, climate change will also reduce the effectiveness of host plant resistance, transgenic plants used for pest management. So there is a need to develop an information on the likely effects of climate change on natural enemies and subsequently developing the technologies for future pest management. By thoroughly understanding the implications of climate change on food security and nutrition, policymakers, researchers and stakeholders can develop strategies to enhance resilience, mitigate risks, and ensure sustainable food production systems for future purpose. This chapter explores the various dimensions of the climate food security challenges and highlights the importance of addressing these challenges through integrated approaches and innovative solutions.

Impact of changing climate scenario towards food security

As we all know, after a decade of works, in 2015 the United Nations Member States outlined a clear path towards peace and prosperity for people and the planet, now and into the future by the name of "The 2030 Agenda for Sustainable Development" with17 Sustainable Development Goals (SDGs) and 169 targets at its heart (United Nations, 2015). Despite the global efforts, food insecurity and malnutrition are still major threat lines in many developing countries due to the unpredictable devastating changes in the climate.In the global population, about 9.2% (735 million people) were facing chronic hunger and 29.6% (2.4 billion people)wereunder moderate to severe food insecurity alongside withmalnutrition in children under the age of 5 such as stunting (148 million approx.) and overweight (37 million approx.) in the year 2022(United Nations, 2023). Hence, the world is in an urgency to mitigate the cascading impacts of climate change on food security and nutrition.

The multifaceted relationship between food security and climate change

The agriculture food system is the linchpin of the farm-to-fork continuum which is linked with numerous environmental and socioeconomic factors including climate. The unpredictable changes in the climatic conditions (temperature, precipitation, wind patterns and other measures of climate) exert their influence on the food system at an increasing rate which consecutively impinges food security. Food security is a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (The World Food Summit, 1996). This definition divulges four dimensions of food security viz., food availability, accessibility, utilization and stability of the above three. These four dimensions have an adverse relationship with climate change in both direct and indirect ways as detailed below in this section.

Present scenario of biopesticides

Bioagents can be formulated as biopesticides wherein the cell count and viability of the organism is highly sufficient for their introduction to various crops and application in the field (Van, 2012). Globally, the market for biopesticides is $2 billion in 2016 which is expected to reach $4 billion by 2024 at a growing CAGR (Compound annual growth rate) of 8.8% from 2016 to 2024. While considering the Indian market, the market is around US$ 23.92 million in 2015 with a CAGR of 20.2% since 2010-2020(Nandani Shukla et al., 2019). In the past two decades, the biopesticides had attained a tremendous growth and its annual growth rate is estimated as 16% whereas that of synthetic pesticides is around 3% only (NAAS, 2013).

Any microorganisms developed as biopesticides should be registered in the schedule of Gazette of India with Central Insecticide Board, Faridabad, under the insecticide act 1968. In india, more than 63 registered private companies are manufacturing the biopesticides in which some major companies are Pest Control (Pvt) Ltd., Multiplex Biotech Ltd., International Panacea, Biotech International Ltd., T. Stanes. There are few genera of microorganisms being used for the formulation of biopesticides including*Trichoderma* spp., *Pseudomonas fluorescens* and spp., *Bacillus* spp., *Streptomyces* spp., *Ampelomyces quisqualis, Agrobacterium radiobacter*, *Coniothyrium* spp., nonpathogenic *Fusarium* and toxigenic *Aspergillus niger* (Singh. et al., 2014 and Keswani et al., 2015). Furthermore, *Bacillus frmus* and *Purpureocillium lilacinum* are the only approved bio control agents to use against nematodes (Pertot et al., 2015).

Mechanism of action of biocontrol agents against plant pathogen

Microbial biological control agents (MBCAs) are used on crops to control plant diseases through a variety of mechanisms. The mode of action of biocontrol agents involves both direct and indirect mechanisms. The direct mode of action such as antibiosis, parasitism, reactive oxygen species production, cell wall degrading enzymes, etc., and the indirect mechanism includes competition and induced resistance which has been depicted clearly in Fig.1.

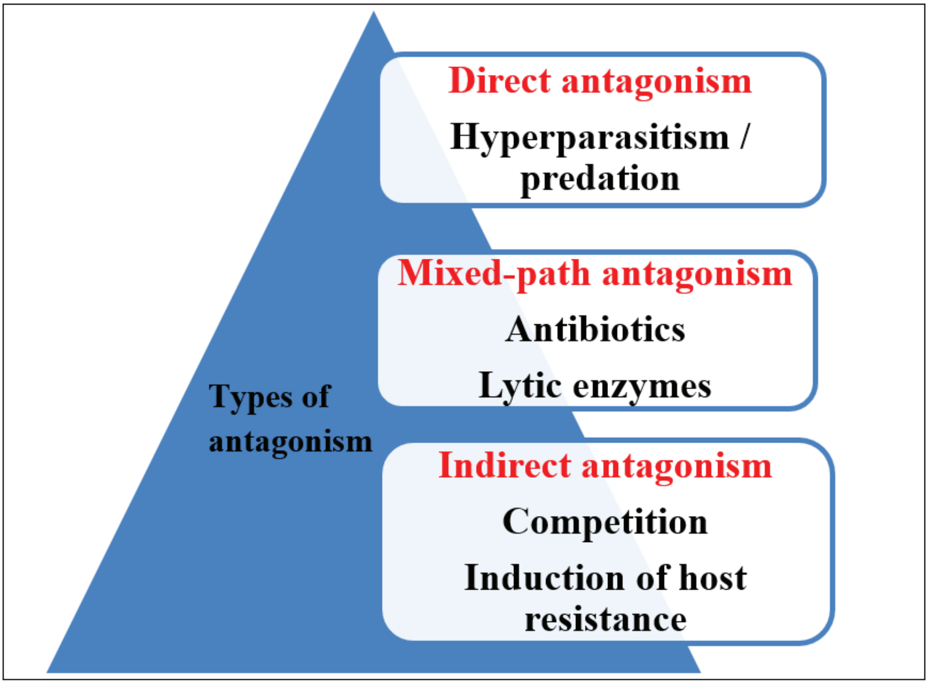

Figure 1: Mode of action of BCAs

(i) Hyperparasitism

It involves a pathogen being specifically attacked by a particular biocontrol agent, which kills it or its parasites. Hyperparasitism can be classified into four types such as Obligatory bacterial pathogens, hypoviruses, facultative parasites and predators. For example, the bacterial pathogen *Pasteruria penetrans* which is an obligate biocontrol agent. Hypoviruses is a virus that infects fungi. For example,the chestnut blight causing fungi,*Cryphonectria parasitica* can be hyperparasites by the virus CHV1 that help in reduction of disease-producing capacity of a pathogen. Several fungi, including *Acremonium alternatum, Acrodontium crateriforme, Ampelomyces quisqualis, Cladosporium oxysporum*, and *Gliocladium virens*, can parasitize powdery mildew infections which is an example for the facultative fungi parasiting other fungal pathogens (Kiss, 2003). Pal et al., (2006) identified hyperparasitism as the most prevalent and direct form of antagonism. *Trichoderma harzianum* has high mycoparasitic activity against *Rhizoctonia solani* hyphae (Altomare et al., 1999).

Mycoparasitism is controlled by enzymes. Harman (2000) identified the role of chitinase and β-1, 3 glucanase in Trichoderma-mediated biological control.

Changes in gene structure can result in the synthesis of various enzymes. *Trichoderma* strain lacking endochitinase had lower control over *Botrytris cineria* but higher control over *Rhizoctonia solani*.

(ii) Antibiosis

The condition in which one or more metabolites (it can be either antibiotics or volatile compounds) are secreted by an organism that shows harmful effects on other organisms. Microorganism-produced antibiotics have been found to effectively control plant infections and illnesses. *Pseudomyza flocculosa* is one of the biocontrol agents which is effective against powdery mildews but its mode of action is quite difficult to find. The recent electron microscopic studies revealed that this antagonist did not penetrate powdery mildew cells but can induce rapid cell destruction (Belanger et al.,2012). The following table provides examples of antibiotics used to inhibit plant pathogens. Antibiotics have been demonstrated to effectively limit the growth of target pathogens *in-vitro* and *in-situ.* The antibiotics should be produced in sufficient quantities so that they can act effectively as shown in below Table 2.

Table 2: Representation of source of antibiotics and their target pathogen

Antibiotic	Source	Target Pathogen	Disease	Reference
2,4-diacetyl-phloroglucinol	*Pseudomonas fluorescence F113*	*Pythium* spp.	Damping off	Shanahan et al., (1992),
Agrocin 84	*Agrobacterium radiobacter*	*Agrobacterium tumefaciens*	Crown gall	Kerr (1980)
Bacillomycin D	*Bacillus subtilis AU195*	*Aspergillus flavus*	Aflatoxin contami-nation	Moyne et al., (2001)
Bacillomycin, fengycin	*Bacillus amyloliquefaciens FZB42*	*Fusarium oxysporum*	Wilt	Koumoutsi et al., (2004)
Xanthobaccin A	*Lysobacter sp. strain SB-K88*	*Aphanomyces cochlioides*	Damping off	Islam et al., (2005)
Gliotoxin	*Trichoderma virens*	*Rhizoctonia solani*	Root rots	Wilhite et al., (2001)
Herbicolin	*Pantoeaagglo-merans C9-1*	*Erwinia amylovora*	Fire blight	Sandra et al., (2001)
Iturin A	*B. subtilis QST713*	*Botrytis cinerea* and *R. solani*	Damping off	Paulitz and Belanger (2001), Kloepper et al., (2004)

Antibiotic	Source	Target Pathogen	Disease	Reference
Mycosubtilin	*B. subtilis BBG100*	*Pythium aphanidermatum*	Damping off	Leclere et al., (2005)
Phenazines	*P. fluorescens 2-79 and 30-84*	*Gaeumannomyces graminis var. tritici*	Take-all	Thomashow et al., (1990)
Pyoluteorin, pyrrolnitrin	*P. fluorescens Pf-5*	*Pythium ultimum and R. solani*	Damping off	Howell and Stipanovic (1980)
Zwittermicin A	*Bacillus cereus UW85*	*Phytophthora medicaginis*	Damping off	Smith et al., (1993)

(iii) Competition

Soils and plant surfaces are often nutrient-limited for microbial growth. To colonize the phyllosphere, microbes must compete for available resources. Pathogen receive nutrients from the host plant surface exudates, leachates, or senesced tissue. Nutrients can also be taken via insect excrement (e.g., aphid honeydew on leaves) and dirt. Indirect evidence implies that pathogen-non-pathogen competition for nutritional resources plays a crucial role in controlling illness prevalence and severity. In particular, the biocontrol agents have a more effective method for absorbing or using the chemical than do the pathogens (Handelsman & Parke, 1989). For instance, microbial growth in alkaline soils may be restricted by iron competition. According to Loper and Buyer (1991), certain bacteria, particularly *fluorescent pseudomonads*, produce siderophores with extremely high affinities for iron that can be used to sequester this scarce resource from other microorganisms and stop their growth. According to some research, siderophores, especially those involving *Pythium* species, have little to no effect on the control of disease (Hamdan et al., 1998). It was reported that the induction of systemic resistance to Fusarium wilt of radish may be facilitated by iron-chelating salicylic acid generated at low iron availability by some *P.fluorescens* strains. Since most resting structures of microbes cannot germinate without certain stimulants due to soil fungistasis, competition for specific chemicals or stimulants for microorganism germination may also develop in soil (Ko & Lockwood, 1970). Some examples of siderophores produced by different fungi and bacteria. The siderophores classified into hydroxymate, catecholate and mixed ligands as given below in the Table 3.

(iv) Induced systemic resistance

ISR may be induced by inoculating plants either with a non-pathogen or with certain natural or synthetic chemical compounds. Systemic acquired resistance (SAR) is the term for the inducible resistance that plants develop to a range of pathogens. SAR can be caused by inoculating plants with a necrogenic pathogen, a nonpathogen, or with specific natural or synthetic chemical compounds (Lam and Gaffney 1993). Defense responses can include physical thickening of cell walls through lignification, callose deposition, accumulation of antimicrobial low-molecular-weight substances (e.g., phytoalexins), and synthesis of different proteins (e.g., chitinases, glucanases, peroxidases, and other pathogenesis-related (PR) proteins) (Hammerschmidt et al, 1984). One can have systemic or localized induced resistance. In systemic acquired resistance, salicylic acid (SA) and non-expressor of pathogenesis-related genes 1 (NPR1) are important participants. When applied to grape leaves or roots, *Trichoderma harzianum* can prevent *Botrytis cinerea* disease on leaves that are geographically far from the site where the biocontrol agent is applied.

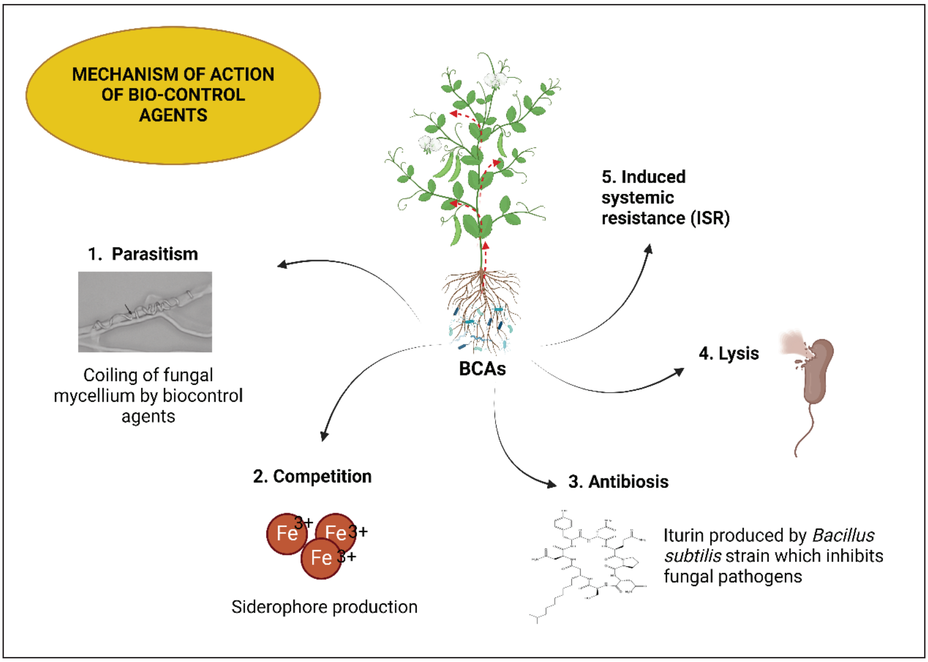

Figure 2: Mechanism of action of Bio-Control agents

Insects

Myco-biocontrol plays an important role in environment by effectively reducing or mitigating insect pests. It is the process of using fungi in biological process to decrease the insect density to attain disease reduction and disease producing activity. For example, *Aschersonia aleyrodes* infects only scale insects and whiteflies. Entomopathogenic fungi includes *Metarhizium anisopliae* and *B. bassiana* are well identified and used as myco-biocontrol agents against agricultural pests worldwide.

Different types of organisms including pathogenic microorganisms such as viruses, bacteria, fungi, protozoa and nematodes have been used in biocontrol agents(Sandhu et al.,2012). *Bacillus* species, including *Bacillus* *thuringiensis* israelensis (Bti) and *Bacillus sphaericus* were discovered to be highly effective against mosquitoes (Revathi et al., 2013). Bti was found to be more harmful to mosquito larvae in 1975 (Goldberg & Margalit, 1977).

Various bacterial species and subspecies, especially *Bacillus, Pseudomonas*, etc., have been established as biopesticides and are primarily used to control insect and plant diseases. Insecticides derived from various subspecies of *Bacillus thuringiensis Berliner* are the most prominent. *B. thuringiensis ssp. kurstaki* and *aizawai* have the highest activity against lepidopteran larvae, while *B. thuringiensis israelensis* targets mosquito larvae, black fly (simuliid), and fungus gnats. *B. thuringiensis tenebrionis* targets coleopteran adults and larvae, including the Colorado potato beetle (*Leptinotarsa decemlineata*), and *B. thuringiensis japon* (Carlton 1993; Copping and Menn 2000). Bt creates crystalline proteins and kills some insect pests, such as lepidopterans. Bt crystalline proteins bind to insect gastrointestinal receptors, determining the target pest.

M. anisopliae Sorokin var. *anisopliae* is a key entomopathogenic fungus. It spreads worldwide through soil and hosts a diverse diversity of insects. Metschnik off first described *Entomophthora anisopliae*, a disease of wheat cockchafers, in 1879. Sorokin later named it *M.anisopliae* in 1883 (Tulloch, 1976). Entomopathogenic fungi and derivatives are employed as microbial insecticides. *M. anisopliae*, a hyphomycete entomopathogenic fungi, is widely utilized for insect pest control and is found worldwide. This species includes numerous strains and isolates from various regions and hosts (Roberts and St. Leger 2004).

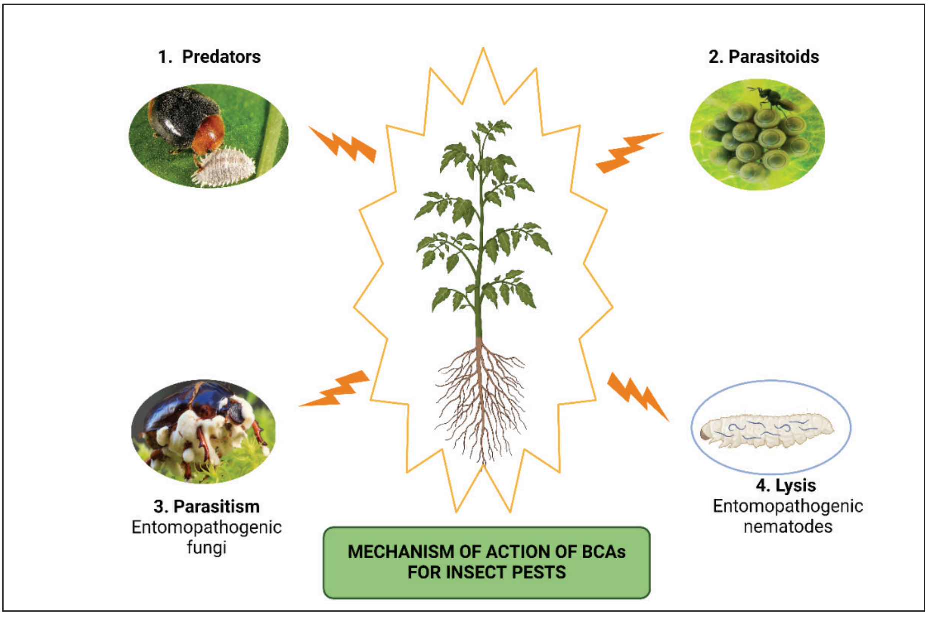

Figure 3: Mechanism of action of Bio-control agents for insect pests

Baculoviruses are double-stranded DNA viruses present in arthropods, mainly insects. Baculoviruses are usually highly pathogenic and have been used efficaciously in their natural form as biocontrol agents against numerous serious insect pests (Moscardi, 1999). Insect protozoan infections are common in the wild and playa crucial role in controlling insect populations (Maddox, 1987). The only species that has been officially recognized and commercially established for grasshoppers are *Nosema locustae* (Henry and Oma 1981) which are pathogenic. Nematodes are one of the newest and most popular biopesticide products. Several efficient endo-molecular nematodes from the genera *Steinernema* and *Heterorhabditis* were identified and used as biocontrol agent against insects in the early 1990s (Copping & Menn, 2000).

Mode of action of Entomopathogenic fungus

Entomopathogenic fungi occupy the largest single group of insect pathogens among microorganisms. Many species which belong to the order Lepidoptera, Coleoptera, Homoptera, Hymenoptera and Diptera are highly susceptible to fungal infections. The mechanism of the mode of action of biocontrol agents against insect pests undergoes infection processes such as conidial attachment with cuticle, formation of an infection structure and penetration of the cuticle. The initiation of mycosis is an attachment of fungal spores to the surface of the cuticle. Once it gets adhered to, it will invade its host through the infection process and it puts pressure on the cuticle by developing appressorium and then penetrating it by infection peg (Sandhu et al.,1995). The penetration peg has to penetrate through the cuticle into the insect body to obtain nutrients for their growth and reproduction. The process involved while penetrating is enzymatic degradation and mechanical pressure. For instance,*M. anisopliae* produced cell wall degrading enzymes while forming an infection structure on *Calliphora vomitoria.* In the case of *Manductasexa,* it involves both biochemical and histochemical processes (Leger et al.,1989).

Mode of action of entomopathogenic nematode

In nematodes, the parasitic cycle is initiated by the infective juveniles (IJs) of third-stage (J3). These nonfeeding juveniles infest suitable insect hosts and enter through the insect's natural body openings like the anus, mouth, and spiracles (Grewal et al., 1997). Once they have entered inside the host, nematodes infest the hemocoel and then release their symbiotic bacteria into the intestine. After that, the bacteria cause septicemia, killing the host within 24–48 hours. The uptake of IJs is rapidly manipulated by the bacteria and decomposed the host tissues. Almost two to three generations of the nematodes are finished within the host cadaver (Pomar & Leutenegger, 1968).

It is well-established that entomopathogenic nematodes can be useful biocontrol agents against several of the major insect pest groups found in stored commodities which include families such as Pyralidae (Shannag and Capinera 2000) and Curculionidae (Duncan and McCoy, 1996).

Mode of action of Baculo virus

For baculoviruses to cause infection, the larva must consume them. Following consumption, they enter the insect's body through the midgut, from which they spread throughout the entire body; however, in certain insects, the infection may just affect the midgut or the fat portion of the body. There are two types of baculoviruses: granuloviruses (GVs) and nucleopolyhedroviruses (NPVs). Whereas occlusion bodies in GVs typically contain a single virus particle, and many virus particles in NPVs. Baculoviruses are occluded, meaning that the virus particles are lodged in a protein matrix, which is a typical characteristic of these viruses. Because they enable the virus to persist outside of the host, occlusion bodies are crucial to the biology of baculoviruses (Cory 2000).Various bioactive compounds have been derived from entomopathogenic fungi that can be commercially useful for field application asgiven in Table 5.

Dynamics of insect pests and pathogens under changing climate

Climate change significantly impacts the dynamics of insect pests and pathogens, influencing their distribution, abundance, and the severity of the diseases they cause. As global temperatures rise, precipitation patterns shift, and extreme weather events become more frequent, the interactions between pests, pathogens, and their hosts are altered in complex ways. Understanding these dynamics is crucial for developing effective management strategies to mitigate the adverse effects on food security and biodiversity.

1. Temperature Effects

Temperature is a critical factor influencing the development, reproduction, and survival of insect pests and pathogens. As global temperatures rise, many pests are experiencing faster development rates, leading to increased population densities and more frequent outbreaks. For instance, the European corn borer (*Ostrinia nubilalis*) can complete an additional generation per year with a 2°C temperature increase, potentially leading to significant maize crop damage in Europe (Porter et al., 1991). Increased temperatures not only shorten the developmental time of the pest but also extend the growing season, providing more opportunities for reproduction and infestation. Similarly, the coffee berry borer (*Hypothenemus hampei*), a major pest in coffee plantations, is expanding its range to higher elevations due to rising temperatures, threatening coffee production in many regions (Jaramillo et al., 2011).As the pest moves into these new areas, it poses a severe threat to the livelihoods of coffee farmers and the global coffee supply chain.

Higher temperatures also influence the virulence and transmission rates of pathogens. Warmer conditions can accelerate the life cycles of many fungal and bacterial pathogens, leading to more severe disease outbreaks. For example, stripe rust (*Puccinia striiformis*) in wheat has become more widespread and severe in regions previously unaffected by the disease due to rising temperatures (Burdon et al., 2006).

2. Precipitation and Humidity

Changes in precipitation and humidity significantly affect the dynamics of pests and pathogens. These environmental factors can either create favourable conditions for the proliferation of pests and diseases or exacerbate plant stress, leading to increased vulnerability. For example, the impact of increased humidity on late blight (*Phytophthora infestans*) in potatoes and tomatoes. Late blight thrives in wet and humid conditions, leading to devastating crop losses. The disease can spread rapidly under favourable conditions, causing significant damage to both potato and tomato crops worldwide.

Similarly, the severity of rice blast disease (*Magnaporthe oryzae*) is closely linked to high humidity and rainfall. Research has shown that increased rainfall and humidity associated with climate change could lead to more frequent and severe outbreaks of rice blast, posing a threat to global rice production and food security (Webster et al., 2002). On the other hand, drought conditions can stress plants, making them more susceptible to pest infestations and diseases. Stressed plants often produce fewer defensive compounds, making them easier targets for pests. Furthermore, drought indirectly affects pest dynamics by altering the competitive balance between pest species and their natural enemies. For instance, drought conditions linked to increased outbreaks of the mountain pine beetle (*Dendroctonus ponderosae*) in North American forests, leading to widespread tree mortality (Bentz et al., 2010).

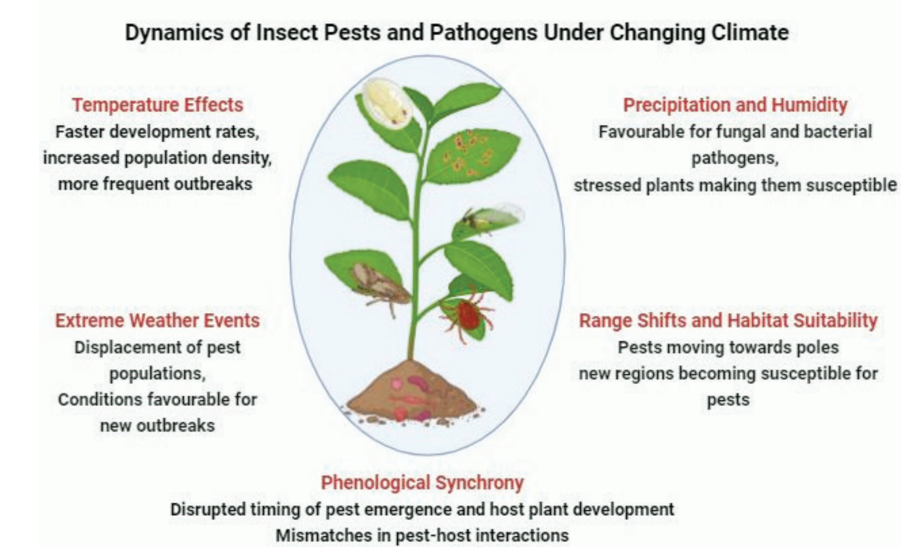

Figure 4: Dynamics of Insect pests and Pathogens under changing climate

3. Extreme Weather Events

Extreme weather events, such as hurricanes, floods, and droughts, can have profound and often unpredictable effects on pest and pathogen populations. These events can cause immediate destruction and displacement of pest populations, but they can also create conditions favourable for new outbreaks. For example, hurricanes can disperse pests over large distances, leading to the establishment of new populations in previously unaffected areas.Floods can also have complex effects on pest and pathogen dynamics. While they can directly kill pests through drowning, they can also create favorable conditions for certain pathogens and secondary pests. Flooded areas often experience increased humidity, which can promote the growth of fungal pathogens.

For example, floods can lead to outbreaks of the rice water weevil (*Lissorhoptrus oryzophilus*) in rice paddies. The larvae of this pest thrive in flooded conditions, feeding on the roots of rice plants and causing significant yield losses. Flooding can also promote the spread of bacterial blight (*Xanthomonas oryzae*) in rice, as the pathogen spreads more easily in waterlogged soils (Ziska et al., 2011).Similarly, drought conditions can exacerbate infestations of spider mites (Tetranychidae) in crops. These pests thrive in hot, dry conditions, and drought-stressed plants are less able to mount effective defenses. Research has shown that spider mite populations can increase dramatically during drought periods, leading to significant damage in crops such as cotton and soybeans (Hance et al., 2007).

4. Phenological Synchrony

Climate change can disrupt the phenological synchrony between pests, pathogens, and their hosts. Phenology refers to the timing of seasonal activities of organisms, such as flowering in plants or breeding in animals. Climate changes can lead to mismatches in the timing of pest emergence and host plant development. These mismatches can significantly impact the interactions between pests, pathogens, and their hosts, leading to altered pest dynamics and potential crop losses.

For instance, the gypsy moth (*Lymantria dispar*), a significant pest of hardwood forests in North America, experiences phenological mismatches with its host trees, resulting in reduced larval survival when larvae emerge too early or late relative to leaf-out (Logan et al., 2003). Similarly, the mountain pine beetle (*Dendroctonus ponderosae*) benefits from earlier springs and warmer temperatures, allowing for earlier adult emergence and extended activity periods, thereby completing more generations per year and increasing tree mortality in North American pine forests (Raffa et al., 2008). In apple orchards, the codling moth (*Cydia pomonella*) shows earlier emergence and prolonged activity due to warmer temperatures, which can increase the number of generations per year; however, mismatches in phenology can affect their ability to find suitable oviposition sites (Tobin et al., 2008).

5. Range Shifts and Habitat Suitability

Climate change is causing many pests and pathogens to shift their ranges poleward and to higher elevations. These range shifts are driven by changes in temperature, precipitation, and habitat suitability. As pests and pathogens move into new areas, they can encounter new hosts and ecosystems, leading to novel interactions and potentially severe impacts on agriculture and natural ecosystems. Bebber et al., (2013) reported that crop pests and pathogens are moving toward the poles at an average rate of 2.7 km per year, a trend that poses new challenges for pest management as these organisms invade previously unaffected areas.

The expansion of the southern pine beetle (*Dendroctonus frontalis*) into the northeastern United States is another example of range shifts driven by climate change. Historically limited by cold winters, this pest is now thriving in areas with milder temperatures, leading to increased tree mortality and forest management challenges (Lesk et al., 2017). Additionally, the pine processionary moth (*Thaumetopoea pityocampa*) has been moving northward in Europe, facilitated by warmer winters, and is now threatening pine forests in regions that were previously unsuitable (Battisti et al., 2005). In Asia, the diamondback moth (*Plutella xylostella*), a significant pest of cruciferous crops, has shown a marked expansion into northern regions, including parts of China and Korea, due to rising temperatures.

Furthermore, the olive fruit fly (*Bactrocera oleae*), which severely impacts olive production, is expanding its range to higher altitudes and latitudes in response to climate warming. This expansion threatens new regions that were previously unsuitable for the pest, complicating olive pest management strategies (Daane et al., 2008). Few examples of pest and pathogens that as influenced by the changing environmental conditions were listed below in Table 6.

Table 6. Pest and pathogens are influenced by the changing environmental conditions

S. No	Pest/ Pathogen	Climate change impact	Description	Reference
1.	Fungal pathogens (rusts, mildews)	Altered precipitation patterns and increased humidity	Changes in precipitation patterns, such as increased rainfall and humidity, can lead to higher incidence and severity of fungal diseases in cereals.	Chakraborty & Newton (2011)
2.	Various pests and pathogens	Extreme weather events	Extreme weather events, including hurricanes and floods, can displace pest populations, leading to new outbreaks and favourable conditions for pathogen spread.	Rosenzweig et al., (2001)

S. No	**Pest/ Pathogen**	**Climate change impact**	**Description**	**Reference**
3.	Bark beetles (*Dendroctonus* spp.)	Increased temperature and drought stress	Higher temperatures and drought conditions have led to increased bark beetle outbreaks in North American forests, benefiting from weakened host trees and expanded habitats due to warmer winters.	Harrington et al., (2001)
4.	Spruce bark beetle *(Ips typographus*)	Warmer temperatures and extreme weather events	Warmer temperatures and storms have increased the frequency and severity of spruce bark beetle outbreaks in European forests, causing significant tree mortality and economic losses.	Griessinger et al., (2012)
5.	Hemlock woolly adelgid (*Adelges tsugae*)	Milder winters and longer growing seasons	Milder winter temperatures and longer growing seasons facilitate the spread and establishment of the hemlock woolly adelgid in previously inhospitable northern regions, threatening hemlock forests.	Stange & Ayres (2010)
6.	Tomato yellow leaf curl virus (TYLCV)	Increased temperature and altered precipitation	Higher temperatures and altered precipitation patterns increase the spread and severity of TYLCV, affecting tomato crops globally.	Canto et al., (2009)

S. No	Pest/ Pathogen	Climate change impact	Description	Reference
7.	Pine processionary moth (*Thaumetopoea pityocampa*)	Warmer temperatures	Warmer winter temperatures have expanded the range of the pine processionary moth northward in Europe, leading to increased defoliation of pine forests.	Jactel et al., (2012)
8.	Stripe rust (*Puccinia striiformis*)	Increased temperature	Higher temperatures have led to more severe and widespread outbreaks of stripe rust in wheat, particularly in regions previously unaffected by the disease.	Burdon et al., (2006)
9.	Insect pests (e.g., aphids)	Global warming	This study predicts that crop losses due to insect pests could increase substantially with global warming, as higher temperatures enhance insect metabolic rates and population growth.	Deutsch et al., (2018)
10.	Invasive pests (e.g., emerald ash borer)	Climate change-induced habitat suitability	Climate change is likely to increase the habitat suitability for invasive pests like the emerald ash borer, exacerbating their impacts on native ecosystems and biodiversity.	Dale et al.,(2017)
11.	*Phytophthora infestans* (potato late blight)	Increased temperature and humidity	Climate change is expected to increase the risk of potato late blight in many regions due to higher temperatures and humidity levels, challenging global potato production.	Bebber et al., (2014)

Management implications for insect pests and pathogen under changing climate

Indirect effects of climate change include interactions between and among insect species, such as interactions with their habitat and with competitors, mutualists, and predators, as well as direct effects on the reproduction, development, survival, and dissemination of pests.Because they are poikilothermic, temperature fluctuations have a big effect on insects. Insect behaviour, distribution, development, and reproduction are all influenced by temperature. Insect physiology is significantly impacted by temperature variations, with a doubling in metabolic rate for every 10 degrees Celsius increase.For instance, pests like the cotton bollworm and corn earworm expand their range and become more resilient to winter, which poses serious problems for crop yield and pest management in maize, a major food crop in the world.Their overwinter survival rate has been risen due to the phenomena of global warming.There may be more generations of insects every growing season as a result of some insects' shorter developmental times due to rising temperatures.

1. Elevated CO_2 concentration (ECC)

ECC results in higher rates of photosynthesis, stomatal openings, and a reduction in water loss through transpiration. The amount of carbohydrates in leaves rises along with CO_2 levels, whereas nitrogen levels fall. ECC can change the amount of nutrients that plants receive, especially protein, which can affect the plant's defense mechanisms against insects. ECC increases salicylic acid (SA) and decreases the buildup of jasmonic acid (JA), the defense hormone, in plants. For example, by inhibiting JA accumulation, ECC has been demonstrated to reduce tomato resistance to the cotton bollworm *Helicoverpa armigera.* ECC can affect insect pest population size, growth, fertility, and rate of food consumption. Major pests like termites and cockroaches release carbon dioxide into the atmosphere, contributing to global warming. Following digestion, termites release carbon dioxide into the atmosphere (Sugimoto et al., 2000). Every degree of global warming causes an increase in the lifecycle of bugs. Plants responded differently to changes in CO2 content, which may have an impact on host plant selection in future, while Goverde and Erhardt (2003) found that variations in the nutrient content of the plants led to longer days for the development of larvae.

2. Elevated temperature:

Because of their very sensitive physiology, insects typically double in metabolic rate for every 10 degrees Celsius increase in temperature. In this regard, numerous studies have demonstrated that rising temperatures typically hasten the consumption, growth, and migration of insects. These effects can then have an impact on population dynamics through changes in fecundity, survival, generation duration, population size, and geographic range. Some species can flourish and procreate quickly, while species that are unable to evolve and adapt to warmer temperatures typically struggle to sustain their populations. Temperature influences metabolism, metamorphosis, motility, and host availability, all of which impact the likelihood of alterations in the dynamics and population of pests. Aphids, for instance, are less vulnerable to the aphid alarm pheromone that they typically emit in response to insect predators and parasitoids in warmer climates, which may result in a rise in predation. The main environmental elements that control whitefly populations are temperature, general humidity, and precipitation. Elevated temperature and high humidity have a positive correlation with the growth of whitefly populations. Recently around 1100 insect species discovered that, by 2050, 15–37% of these species would go extinct owing to climatic change brought on by global warming. Expanding geographic range, higher overwintering population survival rates, increased risk of invasive insect species introduction, increased incidence of insect-transmitted plant diseases due to insect vectors' rapid reproduction and expanded range, decreased efficacy of biological control agents like natural enemies, etc. are some of the general effects of global warming on insect dynamics (Skendzic et al., 2021).

3. Climate-smart pest management (CSPM)

A cross-sectoral approach known as "climate-smart pest management" (CSPM) aims to lower crop losses due to pests, enhance ecosystem services, lower greenhouse gas emissions per unit of food produced, and increase agricultural systems' resilience to climate change. CSPM also helps mitigate

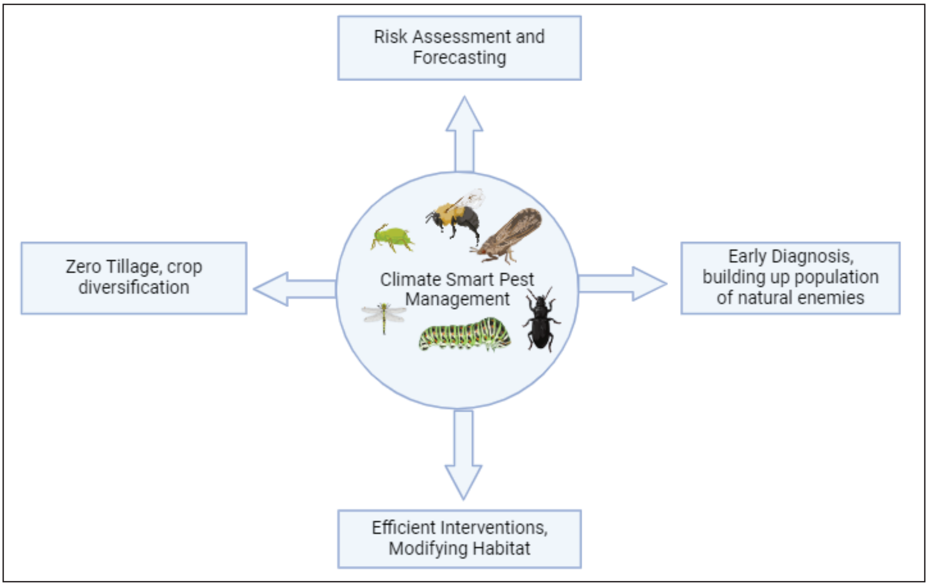

Figure 5: Climate Smart Pest Managemen

climate change by improving the overall greenhouse gas (GHG) balance. For CSPM to be effective, it must be viewed as a component of a larger CSA intervention, with pest management being one of its primary goals, rather than as a stand-alone remedy.To improve the health of their farms and the surrounding environment and reduce vulnerability to disruption caused by pests, CSPM will arm farmers with the knowledge and tools they need to implement pest prevention practices (such as crop diversification, creating natural habitats, and carefully managing water). As a result, CSPM promotes organized research and extension assistance and suggests procedures and approaches to guarantee that the services provided by it are appropriate and accessible to all farmers, including those who are frequently overlooked. Integrated soil fertility management, site-specific nutrient management, climate-resilient crop breeding, conservation agriculture, and crop diversification methods are some of the most crucial CSA initiatives for the success of CSPM (Heeb et al., 2019).

Conclusion and Future Thrust

Climate has a significant impact on plant and insect phenology. Rising temperatures are anticipated to encourage the emergence of parasitoids and result in more generations.Additionally, there might be temporal and spatial mismatches between pests and their natural enemies, which would lessen the effectiveness of biocontrol agents. Forecasting these effects without a complete understanding of the tri-trophic relationships between species will be challenging. To improve the implementation of potential biocontrol agents, a combination of technological innovations and gadgets, remote information detection, Geographic Information Systems (GIS), Automatic Weather Stations (AWS), and the Internet of Things (IoTs) can be used.The next generation of GPS, sensors-equipped farming tools, e-tablets, and adaptable apps may be used to track future threshold levels for pests and diseases.From the planning of long-term land uses and the best time and order for crops in a district to the augmentation of systems through the introduction of new natural enemies, predictive models can be utilized to maximize the benefits of biocontrol.Risk evaluation and regulatory clearance for introducing novel genetic lines for biocontrol agents created by a small group of people to boost genetic diversity. This will increase genetic variation and adaptability, potentially reducing the harmful effects of climate change. Investigating biocontrol should be done for “sleeper pests,” or those that have effective biocontrol available abroad and are predicted to become important pests due to climate change.

References

Altomare, C., Norvell, W. A., Björkman, T. H. O. M. A. S., & Harman, G. (1999). Solubilization of phosphates and micronutrients by the plant-growth-promoting and biocontrol fungus *Trichoderma harzianum* Rifai 1295-22. *Applied and environmental microbiology*, *65*(7), 2926-2933.

Battisti, A., Stastny, M., Netherer, S., Robinet, C., Schopf, A., Roques, A.,

& Larsson, S. (2005). Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. Ecological Applications, 15(6), 2084-2096.

Bebber, D. P., Ramotowski, M. A. T., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 3(11), 985-988.

Bebber, D. P., Ramotowski, M. A. T., & Gurr, S. J. (2014). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 4(4), 287-291.

Bélanger, R.R., Labbé, C., Lefebvre, F. & Teichmann, B. (2012) Mode of action of biocontrol agents: all that glitters is not gold. *Canadian Journal of Plant Pathology*, 34(4), 469-478.

Bentz, B. J., Régnière, J., Fettig, C. J., Hansen, E. M., Hayes, J. L., Hicke, J. A., & Seybold, S. J. (2010). Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, 60(8), 602-613.

Burdon, J. J., Thrall, P. H., & Ericson, L. (2006). The current and future dynamics of disease in plant communities. *Annual Review of Phytopathology*, 44, 19-39.

Canto, T., Aranda, M. A., & Fereres, A. (2009). Climate change effects on physiology and population dynamics of insect-transmitted plant viruses. *Global Change Biology*, 15(8), 1884-1894.

Carlton B.C. (1993), Genetics of Bt insecticidal crystal proteins and strategies for the construction of improved strains. In: Duke SO, Menn JJ, Plimmer JR (eds), Pest control with *International Journal of Chemical Studies enhanced environmental safety. ACS symposium series 524*, *American Chemical Society*, Washington, DC. 326-337.

Chakraborty, S., & Newton, A. C. (2011). Climate change, plant diseases, and food security: An overview. *Plant Pathology*, 60(1), 2-14.

Copping L.G., Menn J.J. (2000); Biopesticides: a review of their action, applications and efficacy. *Pest Management Science.* 56:651-676.

Cory J.S. (2000) Assessing the risks of releasing genetically modified virus insecticides: progress to date. *Crop Protection.* 19:779-785.

Daane, K. M., Johnson, M. W., Haviland, D. R., & Pickett, C. H. (2008). Olive fruit fly management. *California Agriculture*, 62(1), 12-15.

Dale, A. G., & Frank, S. D. (2017). Warming and drought combine to increase pest insect fitness on urban trees. *PLOS ONE*, 12(3), e0173844.

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Naylor, R. L. (2018). Increase in crop losses to insect pests in a warming climate. *Science*, 361(6405), 916-919.

Duncan L.W., McCoy C.W. (1996). Vertical distribution in soil, persistence, and efficacy against citrus root weevil (Coleoptera: Curculionidae) of two species of entomogenous nematodes (Rhabditida: Steinernematidae; Heterorhabditidae). *Environmental Entomology.* 25:174-178.

Goldberg L.H., Margalit J. (1977). A bacterial spore demonstrating rapid larvicidal activity against *Anopheles sergentii, Uranotaenia unguiculata, Culex univittatus, Aedes aegypti* and *Culex pipiens.*

Mosquito News. 37:355-358.
Goverde, M., & Erhardt, A. (2003). Effects of elevated CO_2 on development and larval food-plant preference in the butterfly Coenonympha pamphilus (Lepidoptera, Satyridae). *Global Change Biology*, *9*(1), 74-83.
Grewal P.S., Lewis E.E., Gaugler R. (1997). Response of infective stage parasites (Nematoda: *Steinernematidae*) to volatile cues from infected hosts. *Journal of Chemical Ecology.* 23:503-515
Griessinger, J., Seidl, R., & Führer, E. (2012). The effect of climate change on the spruce bark beetle Ips typographus. *Forest Ecology and Management*, 274, 34-44.
Hamdan, H. (1988). *The fluorescent siderophore of Pseudomonas fluorescens: role in suppression of Gaeumannomyces graminis var. tritici and genetic analysis of siderophore production*. Washington State University.
Hammerschmidt, R., Lamport, D. T. A., & Muldoon, E. P. (1984). Cell wall hydroxyproline enhancement and lignin deposition as an early event in the resistance of cucumber to *Cladosporium cucumerinum*. *Physiological plant pathology*, *24*(1), 43-47.
Hance, T., van Baaren, J., Vernon, P., & Boivin, G. (2007). Impact of extreme temperatures on parasitoids in a climate change perspective. *Annual Review of Entomology*, 52, 107-126.
Handelsman, J., & Parke, J. L. (1989). Mechanisms of biocontrol of soilborne plant pathogens. *Plant-microbe interactions (USA)*, *3*.
Harman, G. E. (2000). Myths and dogmas of biocontrol changes in perceptions derived from research on *Trichoderma harzinum* T-22. *Plant disease*, *84*(4), 377-393.
Harrington, R., Fleming, R. A., & Woiwod, I. P. (2001). Climate change impacts on insect management and conservation in temperate regions: Can they be predicted? *Agricultural and Forest Entomology*, 3(4), 233-240.
Henry J.E., Oma E.A. (1981). Pest control by *Nosema locustae*, a pathogen of grasshoppers and crickets. In: Burges HD (ed) Microbial control of pests and plant diseases. Academic, London, 573-586.
Howell, C. R., and Stipanovic, R. D. (1980). Suppression of Pythium ultimum induced damping -off of cotton seedlings by *Pseudomonas fluorescens* and its antibiotic, pyoluterin. *Phytopathology* 70:712-715
Islam, T. M., Hashidoko, Y., Deora, A., Ito, T., and Tahara, S. (2005). Suppression of damping off disease in host plants by the rhizoplane bacterium *Lysobacter sp*. strain SB-K88 is linked to plant colonization and antibiosis against soilborne *peronosporo mycetes*. *Applied Environmental Microbiology*. 71:3786-3796
Jactel, H., & Battisti, A. (2012). Climate change and forest insect pests in Europe. *Biodiversity and Conservation,* 25(4), 883-909.
Jaramillo, J., Muchugu, E., Vega, F. E., Davis, A., Borgemeister, C., & Chabi-Olaye, A. (2011). Climate change or urbanization? Impacts on a traditional coffee production system in East Africa over the last 80 years. *PLOS ONE,* 6(11), e26756.
Kerr, A. (1980). Biological control of crown gall through production of agrocin

84. Plant Dis. 64: 25-30

Keswani, C., Bisen K., Singh V., Sarma B.K., Singh H.B. (2015). Formulation technology of biocontrol agents: Present status and future prospects. Bioformulations: for Sustainable Agriculture. pp 35-52.

Kiss, L. (2003). A review of fungal antagonists of powdery mildews and their potential as biocontrol agents. *Pest Management Science: formerly Pesticide Science*, *59*(4), 475-483.

Ko, W. H., & Lockwood, J. L. (1970). Mechanism of lysis of fungal mycelia in soil. *Phytopathology*, *60*(1), 148-154.

Koumoutsi, A., Chen, X. H., Henne, A., Liesegang, H., Gabriele, H., Franke, P., Vater, J., and Borris, R. (2004). Structural and functional characterization of gene clusters directing nonribosomal synthesis of bioactive lipopeptides in *Bacillus amyloliquefaciens* strain FZB42. *Journal of Bacteriology*. 186:1084-1096

Lam, S. T., & Gaffney, T. D. (1993). Biological activities of bacteria used in plant pathogen control.

Leclere, V., Bechet, M., Adam, A., Guez, J. S., Wathelet, B., Ongena, M., Thonart, P., Gancel, F., Chollet-Imbert, M., and Jacques, P. (2005). Mycosubtilin overproduction by *Bacillus subtilis* BBG100 enhances the organism's antagonistic and biocontrol activities. *Applied Environmental Microbiology* 71:4577-4584.

Leger, R. J. S., Butt, T. M., Goettel, M. S., Staples, R. C., & Roberts, D. W. (1989). Production in vitro of appressoria by the entomopathogenic fungus *Metarhizium anisopliae. Experimental mycology*, 13(3), 274-288.

Lesk, C., Coffel, E., D'Amato, A. W., Dodds, K., & Horton, R. (2017). Threats to North American forests from southern pine beetle with warming winters. *Nature Climate Change*, 7(10), 713-717.

Logan, J. A., Régnière, J., & Powell, J. A. (2003). Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment*, 1(3), 130-137.

Loper, J. E., & Buyer, J. S. (1991). Siderophores in microbial interactions on plant surfaces. *Mol. Plant-Microbe Interact*, *4*(1), 5-13.

Maddox J.V. (1987). Protozoan diseases. In: Fuxa JR, Tanada Y (eds) Epizootiology of insect diseases. Wiley, New York, 417-452.

Moscardi F. (1999). Assessment of the application of baculoviruses for control of Lepidoptera. Annual Review of Entomology, 44:257-289.

Moyne, A. L., Shelby, R., Cleveland, T. E., and Tuzun, S. (2001). Bacillomycin D: an iturin with antifungal activity against *Aspergillus flavus*. J. *Applied Microbiology*. 90:622-629.

NAAS, (2013). Biopesticides – quality assurance, Policy Paper No. 62, National Academy of Agricultural Sciences, New Delhi, p. 20.

Paulitz, T. C., and Belanger, R. R. (2001). Biological control in greenhouse systems. *Annual Review Phytopathology* 39:103-133

Pertot, I., Alabouvette, C., Esteve, E.H., Franca, S. (2015). The use of microbial biocontrol agents against soil-borne diseases. Retrieved from European Commission EIPAGRI Focus Group. 2015.

Pomar G.O. Jr, Leutenegger R. (1968) Anatomy of the effective and normal third stage juveniles of *Steinernema carpocapsae* Weiser (*Steinernematidae*: Nematoda). *Journal of Parasitology*. 54:340-350.

Porter, J. H., Parry, M. L., & Carter, T. R. (1991). The potential effects of climatic change on agricultural insect pests. *Agricultural and Forest Meteorology*, 57(1-3), 221-240.

Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. A., Turner, M. G., & Romme, W. H. (2008). Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience,* 58(6), 501-517.

Revathi K, Chandrasekaran R, Thanigaivel A, Kirubakaran S.A, Sathish-Narayanan S, Senthil-Nathan S. (2013). Effects of *Bacillus subtilis* metabolites on larval *Aedes aegypti* L. *Pesticide and Biochemical Physiology.* 107:369-376.

Roberts D.W., St Leger R.J. (2004). *Metarhizium* spp., cosmopolitan insect-pathogenic fungi: mycological aspects. *Advancement of Applied Microbiology* 54:1-70.

Rosenzweig, C., Iglesias, A., Yang, X. B., Epstein, P. R., & Chivian, E. (2001). Climate change and extreme weather events: Implications for food production, plant diseases, and pests. *Global Change & Human Health*, 2(2), 90-104.

Sandhu, G. S., Kline, B. C., Stockman, L., & Roberts, G. D. (1995). Molecular probes for diagnosis of fungal infections. *Journal of clinical microbiology*, 33(11), 2913-2919.

Sandhu, S. S., Sharma, A. K., Beniwal, V., Goel, G., Batra, P., Kumar, A., & Malhotra, S. (2012). Myco-biocontrol of insect pests: factors involved, mechanism, and regulation. *Journal of pathogens*, *2012*.

Sandra, A. I., Wright, C. H., Zumoff, L. S., and Steven, V. B. (2001). *Pantoea agglomerans* strain EH318 produces two antibiotics that inhibit *Erwinia amylovora* in vitro. *Applied Environmental Microbiology* 67:282-292.

Shanahan, P., O'Sullivan, D. J., Simpson, P., Glennon, J. D., and O'Gara, F. (1992). Isolation of 2,4-Diacetylphloroglucinol from a *fluorescent pseudomonad* and investigation of physiological parameters influencing its production. *Applied Environmental Microbiology* 58:353-358.

Shannag H.K., Capinera J.L. (2000). Interference of *Steinernema carpocapsae* (Nematoda: *Steinernematidae*) with *Cardio chilesdiaphaniae* (Hymenoptera: Braconidae), a parasitoid of melonworm and pickleworm (Lepidoptera: Pyralidae). *Environmental Entomology,* 29:612-617.

Singh, H.B., Singh A., Sarma, B.K., Upadhyay D.N. (2014). *Trichoderma viride* 2% WP (Strain No. BHU–2953) formulation suppresses tomato wilt caused by *Fusarium oxysporum* f. sp. lycopersici and chilli damping–off caused by *Pythium aphanidermatum* effectively under different agroclimatic conditions. International Journal of Agricultural Environment and Biotechnology 7:313–320.

Skendžic, S., Zovko, M., Živkovic, I. P., Lešic, V., & Lemic, D. (2021). The impact of climate change on agricultural insect pests. Insects. 2021; 12: 440.

Smith, K. P., Havey, M. J., and Handelsman, J. (1993). Suppression of cottony leak of cucumber with *Bacillus cereus* strain UW85. *Plant Diseases* 77:139-142.

Stange, E. E., & Ayres, M. P. (2010). Climate change impacts: Insects. In: Climate Change and Global Warming: Understanding the Human Impact. *Springer Science & Business Media.*

Sugimoto, A., Bignell, D. E., & MacDonald, J. A. (2000). *Global impact of termites on the carbon cycle and atmospheric trace gases* (pp. 409-435). Springer Netherlands.

Thomashow, L. S., Weller, D. M., Bonsall, R. F., and Pierson, L. S. III. (1990). Production of the antibiotic phenazine-1-carboxylic acid by *fluorescent pseudomonas* in the rhizosphere of wheat. *Applied Environmental Microbiology* 56:908-912.

Tobin, P. C., Nagarkatti, S., Loeb, G., & Saunders, M. C. (2008). Historical and projected interactions between climate change and insect pests: Implications for human health, agriculture, and forestry. *Journal of Forestry*, 106(4), 191-196.

Tulloch M. (1976). The genus Metarhizium. Trans Br Mycol Soc.; 66:407-41.1

United Nations (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015. New York.

United Nations (2023). *The Sustainable Development Goals Report 2023*: Special Edition. United Nations Department of Economic and Social Affairs Statistics Division (UN DESA). https://unstats.un.org/sdgs

Van Lenteren, J.C. (2012). The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake. *BioControl* 57, 1–20

Webster, R. K., Gunnell, P. S., & Lee, F. N. (2002). Compendium of rice diseases. *American Phytopathological Society*.

Wilhite, S. E., Lunsden, R. D., and Strancy, D. C. (2001). Peptide synthetase gene in *Trichoderma virens*. *Applied Environmental Microbiology* 67:5055-5062.

World Food Summit. (1996). Rome Declaration on World Food Security. Rome, FAO.

Ziska, L. H., Runion, G. B., & Tomecek, M. (2011). Climate change and agronomic crop insect pests: Modeling different scenarios of temperature, CO2, and water availability. In Global Climate Change and Extreme Weather Events: Understanding the Contributions to Infectious Disease Emergence: Workshop Summary. National Academies Press.