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Synergistic interactions between chemical and biological pest Control agents

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Abstract

Sustainable pest and disease management is increasingly important as agriculture faces growing environmental and biological challenges. Semiochemicals play a vital role in integrated pest management by attracting, repelling, or manipulating insect behavior and enhancing the effectiveness of biological control agents, including natural predators and entomopathogenic microorganisms. While plant-derived semiochemicals have been successfully used in field applications such as trap cropping and push–pull strategies, their integration with microbial biocontrol agents offers additional potential for pest suppression. This review highlights the synergistic interactions between semiochemicals, phytochemical biopesticides, and beneficial microbes such as *Bacillus*, *Pseudomonas*, and *Trichoderma*. Plant-derived compounds, including alkaloids and essential oils, can strengthen plant defenses and improve microbial efficacy against pests and pathogens. Advances in microbial formulations and biodegradable delivery systems further support the development of environmentally friendly crop protection strategies. Future research should focus on species-specific applications and the integration of these biological tools into sustainable pest management programs.

Keywords: Microbial biocontrol, phytochemical biopesticides, sustainable agriculture, crop protection.

1. Introduction

The systematic regulation of chemical, biological, and mechanical elements that collectively impact crop development, yield, and quality is part of sustainable crop protection. Sustainable agriculture, according to Montesinos, is a system that effectively uses biocontrol products such as natural antimicrobial medications for disease and insect suppression and biopesticides made from natural sources as opposed to manufactured chemicals. Because of this, modern pest control goes beyond conventional techniques, emphasising the vital role microorganisms play in enhancing the general wellness, resistance, and production of crop plants. A synergistic combination of phytochemical biopesticides and microbial biocontrol agents offers various benefits for long-term crop protection in pest management. Compared to single-agent applications, such integrated techniques can improve disease suppression, lessen the evolution of

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resistance, and preserve ecological balance [1] For example, using neem (Azadirachta sativa) extracts in conjunction with Bacillus thuringiensis has increased lepidopteran pest management while lowering the necessary microbial dose. Similarly, antifungal drugs' effectiveness against Botrytis cinerea was greatly enhanced by formulations that combined Trichoderma with the oils of the plants Cymbopogon citratus (lemongrass), or Rosmarinus officinalis (rosemary). together with Rhizoctonia solani. By reducing chemical input and improving environmental safety, these examples demonstrate how synergistic approaches not only increase biocontrol performance but also promote long-term sustainability. This sustainable strategy incorporates ecologically friendly pest and nutrient management strategies, prudent conservation of essential agricultural resources, and thorough pollution control approaches.By focusing on these eco-friendly techniques, we can create a more balanced agro-ecosystem and guarantee that agricultural methods not only promote productivity but also protect the planet's health and the welfare of future generations. Investigating alternate bio-based sources of sustainable plant protection has received more attention in recent years. Significant advancements in microbial microorganisms have been made possible by advanced biotechnology techniques.

2. Phytochemical Sources

Phytochemicals are naturally occurring molecules derived from plants that function as both principal and secondary compounds and provide protection against a range that are biological and environmental stressors. A vital component of Integrated Pest Management Phytochemical biopesticides are often safer and more target-specific than traditional artificial pesticides (Integrated Pest Management). Two methods are typically used in bioprospecting for new phytochemical substances.2) The first involves determining whether phytochemical pathways are responsible for specific biologicalfunctions, including insect repellency. One such example is azadirachtin, which is the active ingredient in repellents made from neem. The second uses traditional plant formulations that have been shown to be effective against agricultural pests and is based on ethnobotanical knowledge The most effective phytochemical biopesticides are frequently derived from medicinal plants, but they can be obtained from a variety of plant matrices. Essential oil-rich waste products are also useful sources of bioactive components that can be mixed in certain ratios to increase effectiveness. Allergic along with aromatic compounds such as essential oils, and alkaloids are the primary types of bioactive phytochemicals that interfere with pests' neurological systems and enzymatic activity. Almost every plant organ contains essential oils, which are crucial for the body's defence against infections and herbivores [3]. Their interactions with target species' lipid membranes, which cause cell lysis and death, are primarily responsible for their biological activity. Strong insecticidal, fungicidal, bactericidal, and fumigant properties are displayed by phytochemical extracts and purified fractions, which also biodegrade quickly. The majority of these substances have broad-spectrum effectiveness against pests of agriculture and easily break down into chemicals that are safe for the environment.

3. Microbial Biocontrol Agents.

Even while some microorganisms may potentially function as pathogens, they are essential to the biological management of plant diseases. Microbe biocontrol agents or BCAs lessen a variety of plant diseases and increase plant tolerance to biotic and abiotic stimuli. Viruses that target harmful phytopathogens or insects are among the primary types of BCAs. Pests, fungi like Trichoderma spp., and bacteria like Pseudomonas spp and Bacillus and others. Predation (consumption of target species), parasitic activity (direct exploitation of other microorganisms), antibiosis (production of inhibitory chemicals), and competition for resources and ecological niches are some of the various methods of action that these bacteria use [5]. Furthermore, a large number of BCAs improve plant resistance to disease by inducing systemic defensive reactions. With their broad-spectrum activity, high target specificity, compatibility with integrated pest management (IPM) programs, safety for organisms that are not targets, and adherence to organic farming standards, microbial BCAs are appealing instruments for sustainable agriculture. Due to intricate interactions with native soil and plant microorganisms, their field effectiveness may fluctuate depending on the environmental circumstances. Flowers The persistent difficulty of creating dependable, long-term application solutions continues to draw significant research efforts. Plant disease management biocontrol techniques are divided into two categories: direct interactions (microbe to microbe connections) and indirect connections (host–microbe interactions) [4]. Through receptor competition, signal degradation, inhibition of gene expression, promotion of plant systemic resistance, and inhibition of signaling molecule production, these mechanisms interfere with pathogen activity.

3.1Microbial Biocontrol Agent Types

Microbial biocontrol agents offer enhanced environmental sustainability as an alternative to traditional crop protection techniques. Compared to traditional chemical techniques, microbial biocontrol agents offer a more efficient and sustainable alternative to safeguard plants. Through a variety of methods, including parasites, antibiosis, and the development of systemic resistance, they successfully control infections, enhance plant vigour & soil microbiome balance, & lessen chemical residues & environmental toxicity.However, we recognize that because of their quick curative action, chemical pesticides would still be required in some outbreak or emergency situations. Therefore, the most efficient and environmentally sound approach combines short-term effectiveness with long-term environmental safety when microbial biocontrol agents are incorporated into a systemic pest-management (IPM) framework [4] The most significant microbial agents utilised as biocontrol tools included the species of Bacillus, Pseudomonas specie, and

Trichoderma species as well as which collectively account for about 80% of the global biopesticide market, together with endophytic microbial species and mycorrhizal fungi. Bacillus species, which include the two saprophyte and facultative endoscopic bacteria, stimulate plant growth as fixing exogenous nitrogen in soil, generating extracellular hydrolases that break down pathogen cell walls and solubilising phosphates. Additionally, they produce a variety of additional metabolites, including as periodic lipopeptides & polyketides, which are essential for crop protection due to their antifungal, antiviral, antibacterial, and nematicidal qualities. Bacterial subtilis, Bacillus amyloliquefaciens, Bacillus velezensis (sometimes called Bacillus thuringiensis), and Bacillus amyloliquefaciens are common biocontrol species. Pseudomonas species have long been recognised as useful biocontrol products for a range of agricultural diseases. These bacteria are mostly saprophytic, while they can also colonise the rhizosphere and interior plant tissues. The synthesis of various bioactive secondary metabolites, competition for resources and niches in the environment, and the development of related to pathogenesis (PR) proteins that elicit plant immune responses are their primary modes of action. These include phytohormones, hydrolytic enzymes, insecticidal toxins, cyclic lipopeptides such as siderophores, and antibiotics like 2,4-diacetylphloroglucinol (DAPG). Among the most significant genera of filamentous fungal organisms used in professional biocontrol products are Trichoderma species. [5]. Their methods include solubilizing nutrients, producing secondary metabolites that resemble those of Bacillus and Pseudomonas among others, and causing host plants to develop systemic resistance. Both saprophytic and facultative endophytic fungi are included in this genus; species including Trichoderma virens, Trichoderma harzianum, and Trichoderma atroviride are extensively utilized in a variety of crops. More than 80% of terrestrial organisms have mutualistic relationships with the roots of arbuscular mycorrhizal fungus (AMF), which are obligatory symbionts. Through signaling chemicals like ethylene, salicylic acid, and jasmonic acid, AMF enhances nutrient uptake and triggers plant immunological responses. There are two types of mycorrhizal fungi: arbuscular (AMF) and ectomycorrhizal (ECM). AMF is more frequently employed in biocontrol. Endophytic microbes help plants withstand biotic and abiotic challenges by living in their tissues without harming them. AMF and other microorganisms have been shown in numerous studies to be effective in lowering fungal infections in crops like strawberries. By providing nutrients, producing phytohormones and bioactive chemicals, creating systemic resistance, and vying with pathogens for resources and space, these microorganisms improve plant performance. A number of interconnected elements are essential for the production and functioning of microbiological biocontrol agents. Intrinsic microbial traits, such as rate of expansion, sporulation capacity, gene stability, and ability to colonise plant tissues or the rhizosphere, have a direct impact on field efficacy. Soil kind, the amount of moisture, temperature, and pH are environmental parameters that affect microbial growth, activity, and metabolite production. The efficiency of biocontrol can also be influenced by competition for nutrients or space and the presence of natural bacteria. Furthermore, preserving microbiological viability and longevity of products depends heavily on technological elements including formulating creation, carrier substances, and storage stability [6] Lastly, the general adoption of and integration of biological management techniques in agricultural production systems are determined by agronomic and regulatory standards, such as pesticide compatibility and application scheduling. To guarantee repeatable biocontrol results and to optimum microorganism selection, formulation, and deployment in field settings, it is imperative to comprehend these characteristics [6].

3.2Mechanisms of Action

In order to inhibit plant diseases and improve overall plant resilience, the use of microbial biocontrol substances (also known as BCAs) is essential. The molecular pathways of pathogenicity that biologically active compounds target or disrupt have been thoroughly studied in an expanding corpus of research. Quorum sensing (QS) is a sophisticated communication system that many phytopathogens rely on to regulate the production of virulence indicators [7]. During this process, diffusible signalling molecules accumulate. When they reach a particular concentration, they bind with particular receptors and trigger the expression of genes that induce pathogenicity. One of the most significant and scientifically intricate methods of microbial biocontrol is the induction about systemic resistance (ISR). The plant-mediated defence mechanism known as ISR is triggered by certain beneficial bacteria, such as Bacillus subtilis, Pseudomonas fluorescens, and Trichoderma harzianum. These microorganisms trigger host immunological pathways through signalling molecules including salicylic acid, ethylene, and jasmonic acid, "priming" plants for stronger and faster responses in the event of a pathogen attack. Unlike direct antagonism, ISR boosts the plant's intrinsic the immune system, which simultaneously improves tolerance against multiple pathogens and reduces disease incidence [7].

The effectiveness of biocontrol is also greatly influenced by other processes. Antibiotics, lipopeptides, or volatile chemicals (such as diacetylphloroglucinol, iturin, and surfactin) are substances that prevent the growth of pathogens are produced during antibiosis. Fungi like Trichoderma spp. exhibit parasitism and mycoparasitism, which involves direct attack and the enzymatic breakdown of pathogen cell walls by chitinases and glucanases. Pathogens are kept from taking over the rhizosphere by competition for resources and ecological niches. Lastly, the suppression of pathogen communication signals, or quorum quenching, has become a unique tactic in which helpful bacteria neutralize or break down quorum-sensing molecules, thereby reducing the expression of virulence genes. Collectively, these strategies function either independently or in concert, guaranteeing the resilience and adaptability of microbial biocontrol chemicals in long-term crop protection. Microorganisms have developed a variety of tactics to interfere with or block this communication system in the face of pathogen quorum sensing, which reduces the virulence of the pathogen [8]. These tactics include competitive receptor occupation or antibody binding, suppression bacterial quorum-controlled gene activity that could otherwise increase pathogenicity, enzymatic degradation and deactivation of signalling chemicals, and prevention of signal-molecule production [8]. By utilising intricate trophic networks and interspecies relationships, the application or microbial cooperatives has become a practical strategy to boost the effectiveness of biocontrol systems. Potential microbial partnership incompatibilities, erratic ecological relationships, and the detrimental effects of antimicrobial chemicals produced by particular consortium members affecting others are still issues, though. The phyllosphere, an incredibly dynamic environment, is made up of a range of bacterial, yeast, and fungal communities on the topmost layers of aerial plants. These microbes are incredibly flexible to changes in their surroundings and oftenexhibit hostile action against opportunistic diseases. Biocontrol methods fall into two broad categories: direct microbe-microbe interaction and indirect host- microbe interaction involving the organism in issue. Effective microbial consortia design and formulation require an extensive knowledge of the molecular and molecular underpinnings of these mechanisms, backed by carefully planned laboratory and field research. By achieving dependable disease suppression without sacrificing plant growth or productivity, these methods seek to balance the twin demands of preserving high agricultural output and reducing environmental impact in the face of population growth worldwide. Additionally, a variety of helpful bacteria can cause plants to develop systemic resistance (ISR), boosting immunity through endophytic colonization or elicitor synthesis [9]. They efficiently prime plants against pests and diseases by triggering signal-transduction cascades and hormonal interactions that activate important defense-related genes.

3.3 Advantages and restrictions

These organisms were instances microbial biocontrol compounds (BCAs), which offer ion among others. In spite of these benefits, microbial agents have a few drawbacks. Application to particular pests and illnesses is limited by their limited host specificity, which makes precise diagnosis necessary [10] Furthermore, expensive and complicated procedures Large-scale commercialization is hampered by plants engaged in mass formulation, storage, and culturing. Environmental elements including humidity, temperature, ultraviolet radiation, and soil pH also have an impact on their field efficacy, which can decrease consistency and dependability in a variety of agricultural settings. A methodical comparison of the benefits and drawbacks of microbial biocontrol substances can direct their incorporation into long-term pest management initiatives. highlights the primary advantages and drawbacks found in recent research. Some of these limitations can be lessened and field dependability increased by optimizing formulation methods, encapsulating materials, and carrier systems, according to recent research. Future studies that combine microbial and phytochemical agents have chances to get around restrictions on stability and effectiveness without compromising environmental safety [11] As biodegradable, environmentally friendly substitutes for traditional synthetic agrochemicals, phytochemical biopesticides which are primarily derived from essential oils and crude plant extracts have broad-spectrum effectiveness against a range of diseases, including viruses, fungi, bacteria, insects, and nematodes, offering long-term crop protection that is both safe and efficient [12].

4. Plant-Based Biopesticides

Plants are rich in bioactive phytochemicals that serve a range of biological purposes. These organic compounds, which are essential for both ecological interactions and plant defence, have served as the foundation for the creation of many modern agrochemicals. Secondary metabolites that act as naturally occurring antifeedants and repellents to protect plants from insect pests and predators include alkaline chemicals, aroma compounds, phenolics, saponins, fatty acids, and essential oils [13]. The process of creating phytochemical biopesticides usually consists of the following steps: gathering raw plant material, drying to maintain the chemical's integrity, and extracting the active ingredients using appropriate solvents, like methanol or acetone, to separate the desired bioactive components. These plant-based products are becoming more and more popular as safer and more environmentally friendly substitutes for traditional synthetic pesticides. Approximately 95% of pesticides used worldwide now are chemically manufactured, presenting serious dangers to the environment, wildlife, and human health. Phytochemical biopesticides, on the other hand, provide a number of benefits, such as the ability to degrade low production costs, and abundant raw materials. In general, they are less harmful to animals and work well with IPM (integrated pest management) systems, which promotes sustainable farming methods. Agriculture may move closer to a more robust and environmentally conscious future by putting such eco-friendly solutions into practice. Common plant-based biopesticides exhibit a broad range of bioactivities and are generated from various important botanical sources [14]. Azadirachtin-containing neem (Azadirachta indica) extracts have strong antifeedant, insect growth regulator, and oviposition deterrent properties. Insect nervous systems are targeted by pyrethrum derived from Chrysanthemum cinerariifolium, which prolongs sodium channel activity and causes paralysis. Derris and Lonchocarpus species contain rotenone, which has potent insecticidal effects by interfering with mitochondrial electron transport. By disrupting membranes and preventing spore germination, essential oils from plants like Eucalyptus globulus, Thymus vulgaris (thyme), and Cymbopogon citratus (lemongrass) exhibit antifungal and antibacterial properties. Because they function as preventative measures, agents that inhibit enzymes or signaling disruptors, alkaloids (such as nicotine and caffeine), phenols, and saponins also aid in the reduction of pests.(15) Phytochemical biopesticides are attractive instruments in integrated pest control programs because they exhibit a variety of modes of action, including as neurological damage suppression of growth, repellent qualities, and oxidative stress induction [16].

5. Mechanism of Synergism

5.1 Enhanced Efficiency

Two strategies to lower greenhouse gas emissions—the primary cause of climate change—are energy-efficient business and structural lightweighting. Research suggests that a 10% decrease in vehicle weight could lead to a 5.1% decreased fuel consumption. As one of the largest producers to carbon emissions, the manufacturing sector is actively researching sustainable and energy-efficient manufacturing procedures. In this regard, the aerospace, military defense, and automotive industries have shown a great deal of interest in using lightweight materials like titanium (Ti) and aluminum (Al) as substitutes for traditional steel. However, defects like cracks and porosity are frequently produced by fusion welding Ti/Al dissimilar junctions, endangering the mechanical performance and integrity of the joint(17). Although welding with lasers has been investigated as a substitute, its substantial consumption of energy and toxic emissions make it less practical for environmentally friendly production. Friction stirs welding (FSW), on the other hand, has become a cutting-edge, environmentally responsible solid-state joining method. FSW improves joint strength and ductility by facilitating the creation of nanoscale intermetallic compounds (IMCs) through process parameter optimization. FSW is a very promising method for creating Ti/Al hybrid structures that are both environmentally friendly and energy-efficient because it takes place below the freezing point of these components, eliminating smoke, hazardous gas emissions, and

Relatively low welding speeds are the result of significant axial force, resistance, and spindle torque produced by the tool's penetration into the workpiece in FSW. Reducing energy usage requires increasing welding speed, however preserving the mechanical integrity of the welded joints is still quite difficult. Many studies have been done to find efficient ways to speed up welding without sacrificing joint function(18). To improve process efficiency, a number of methods have been investigated, such as laser-assisted FSW, pulse current-assisted FSW, and tungsten inert gas (TIG) arc-assisted FSW. Although these techniques speed up welding and increase the quality of the joint, their extensive industrial use is limited by their frequent negative effects, which include low energy efficiency, hazardous gas emissions, and possible s

UVeFSW, or ultrasonic vibration-enhanced frictional stirred welding, has become a viable method for more effective and environmentally friendly welding. Ultrasonic vibration (UV) has a high the conversion rate of energy (60–80%) and creates no smoke, arc electromagnetic radiation, or hazardous materials, making it a suitable choice for sustainable production. Yao et al. demonstrated that ultrasound significantly reduces yield and flow stresses during deformation due to plastic by inducing cumulative dislocation movement, also known to serve as acoustic plasticity effect. It's interesting to note that

UVeFSW produces a softening effect comparable to thermal assistance with very little energy.(19) A lot of UVeFSW methods have been developed, most of which concentrate on applying ultrasonic waves to the tool or the workpiece. Our research team has created a UVeFSW system where the ultrasonic instrument is applied immediately above the workpiece and positioned before the weld. This concept is a very practical ultrasonic-assisted FSW method because of its straightforward construction and simplicity of use. Nevertheless, it is yet unknown what basic mechanisms underlie UV coupling in FSW. It is anticipated that a better comprehension of these principles and further UV integration in FSW optimization will improve the connection of dissimilar materials, increase welding efficiency, and encourage only around 25% of the input energy is efficiently used for welding or processing, according to Inacio et al.'s analysis of the energy consumption during the FSW process; the majority is lost to the environment or dissipated via the backing plate. Therefore, increasing the FSW process's energy usage efficiency is crucial for developing energy-sustainable industrial applications. Choi et a(20)l. [identified the least energy consumption point under ideal welding conditions and offered a unique approach for energy-saving processes design] further investigated the relationship between industrial welding specifications, energy combination, and joint performance. In a comparison of the energy usage efficiency of several FSW machines, Buffa et al. found that specialist FSW equipment can greatly increase energy efficiency, providing possible avenues for process optimization. FSW is already well known for being a more energy-efficient option than additive manufacturing or fusion-based welding. Furthermore, a number of studies have demonstrated that UVeFSW significantly increases welding speed, indicating that shorter welding times may result in lower energy usage. Systematic studies measuring the true energy-saving potential of UVeFSW are still scarce, despite these encouraging results and substantial research on joint performance, material behavior, and process optimization. A thorough assessment of the UVeFSW's ecological effectiveness is becoming more and more important as business demand for sustainable and energy-efficient welding technology rises.

This work fills this important gap by being the first to do a thorough analysis of the transfer of energy and transformation performance of UVeFSW. The results show a new benefit: Higher welding speeds are made possible by UV's notable enhancement of the energy rates of conversion, which preserves mechanical qualities. As a result, consumption of electricity and carbon emissions are significantly reduced, making UVeFSW a viable green welding method. The clear relationship between ultrasonic-assisted energy utilization and welding performance is revealed in this work, which offers a solid theoretical basis for UVeFSW's industrial implementation. Additionally, the outcomes accelerate the integration of lightweight materials across industries by opening the door for the next generation of low-carbon, high-efficiency welding procedures.(21) In the end, this study presents

UVeFSW as a strategic enabler of green manufacturing and industrial sustainability as well as an inventive welding solution.

5.2 Reduced resistance

Previously, it has been believed that the most significant The insufficient use of AZM is a factor in the development of resistance bacteria. Resistant organisms develop and spread when a medicine is provided improperly when it comes of dosage or duration. Two approaches have usually been used to combat gonococcal resistance to AZM: The MtrCDE gene efflux pump was overexpressed as a result of the mtrR coding region changes. Furthermore, N. gonorrhoeae's reactivity for AZM is decreased by changes in the genes producing the 23S rRNA component [22]. The drug target is altered by mutations in the rrl alleles of the 23S rRNA gene, which impede macrolide binding to this subunit, or by methylation of the 23S ribosomal subunit, which is associated with the presence of erm genes. The AZM resistance to medicines mechanism's molecular underpinnings inP. aeruginosa has revealed that resistant strains can arise in the biologic community of cystic fibrosis patients due to deletions in the ribosomal target medication in the 23S rRNA genome and overexpression of efflux pumps, specifically mexAB-oprM and mexCD-oprJ [23]. Most antibiotics are inefficient against Enterobacteriaceae because of their intrinsically low permeability, even though AZM's improved permeability and increased intracellular uptake led to its improved efficacy. Because Salmonella, Shigella, Klebsiella, and E. coli all have up to a dozen rrn loci, it seems unlikely that Enterobacteriaceae's 23S rRNA alterations are what lead to macrolide resistance. The acetylation of 23S rRNA, which is caused from methylases produced in erm genes, is the most important mechanism providing resistance to macrolide drugs. These genes have been discovered in mobile elements such as plasmids that contain several erm genes. Another type of modification associated with macrolide resistance constitutes the pseudouridylation of 23S rRNA. This post-translational modification was seen in domain V of the E. coli 23S rRNA [24]. Moreover, alterations in other ribosomal proteins, such as L4 (encoded in the rplD genome) and L22 (encoded in the rplV gene), are associated with the development of resistance to macrolide drugs in Enterobacteriaceae.It is significant to remember that intrinsic resistance to the majority of these antimicrobial drugs has been thought to be caused by the hydrophilic properties of macrolides. Additionally, E. coli AZM-resistant mutants have been shown to overexpress outer membrane protein (OmpW) and chromosomal efflux pumps (AcrAB-TolC) in vitro. The decrease of direct antibacterial effectiveness is frequently caused by bacterial macrolide changes in addition to the previously stated mechanisms. In Enterobacteriaceae, the macrolide structure is hydrolysed and altered by four distinct phosphotransferases represented by mph (A, B, D, and E) and two esterases encoded by ere (A, B) genes. Macrolide resistance can be conferred by short peptides such as 23S rRNA fragments. After interacting with the macrolide, these resistance peptides extract it from the ribosome and initiate a fresh translation of the protein.

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According to studies, C. trachomatis cultivar L2 isolated that had mutations in the rplD gene were less susceptible to AZM and ERY. According to reports, mutations in the L4 protein led to structural changes in the 23S rRNA, especially in domains 2, 3, and V, which disrupt ribosome translation function. Additionally, clinical isolates susceptible to the pathogen have been found to have mutations in the non-conserved area of the protein L22 and the peptidyl transferred region of 23S ribosomal genes. Since 2000, there has been a documented sharp rise of macrolide-resistant Treponema pallidum (T. pallidum) species [24]. A2058G or A2059G mutations in one copy of the 23S rRNA, followed by gene conversion of both rRNA genes, are the two steps in the evolution of macrolide resistance isolates.

The horizontal gene transfer of the efflux pump Mef (E) genes is linked to S. pneumoniae's resistance mechanism. Furthermore, by methylating the A2058 nucleotide of 23S rRNA, streptococcal methylase ErmB can acquire high-level cross-resistance to macrolides. Rarely, other mechanisms, such as mutations in ribosomal proteins L4 or L22 and domain V of 23S rRNA, can also be seen in S. pneumoniae isolates that are resistant to macrolides. Mutations in the 23S rRNA domain II, V (rrl) gene, and ribosomal protein L4 (rplD), and L22 (rplV) genes have provided ample evidence of the genetic mechanism behind the antibiotic resistance of S. aureus strains that originate from patients with cystic fibrosis. Furthermore, the resistance to macrolide in S. aureus strains can result from acquired resistance gene transcripts such msr(A), which encodes an efflux protein, and erm, which encodes a ribosomal methylase. These strains of Salmonella are inherently vulnerable to AZM, despite their inherent resistance to ERY, which is linked to active drug efflux. Mutations in 23S rRNA domain V nucleotides A2058 and A2059 are associated with resistance to macrolides. Furthermore, the alteration of the 50S ribosomal subunit proteins L4 and L22 could be a factor in resistance to macrolide. The presence of an efflux pump that is homologous to the aforementioned efflux mechanism in the bacteria E. coli or other pumping mechanisms makes Haemophiles influenzae strains inherently resistant to macrolide [25]. Higher MICs in some bacteria were linked to mutations in the ribosomal proteins L4 and L22 as well as 23S rRNA.

Mutations in the lpeAB (lpp2879–lpp2880) operon's upstream sequence cause Legionella pneumophila strains to overexpress certain proteins. A three-part efflux pump belonging to the resistance–nodulation– division (RND) family is formed by Lpp2879–Lpp2880 and TolC. Additionally, alterations in 23S rRNA gene sequences and L4/L22 ribosomal amino acids have been found in isolates that are resistant to AZM. Substitutions in domain V of the 23S rRNA gene are the most frequent route for high-level resistance to macrolides in Campylobacter species. In the absence of mutations in 23S rRNA genes, another resistance mechanism is the substitution and insertion of ribosomal proteins. Furthermore, resistance to macrolides is significantly influenced by CmeABC efflux pumps, which belong to the RND transporter family. Together, these three processes support high-level macrolide resistance. Antibiotic exclusion via the major outermost membrane porin (MOMP) is another way that Campylobacter species become resistant to macrolides. Overexpression of MOMP, which is chromosomally encoded by porA, allows Campylobacter species to modify membrane permeability. It was found that E. Coli isolates linked to erm (B) caused by MDR, or multidrug resistance, islands in genomics exhibited a unique mechanism of resistance. Erm(B) reduces the binding of macrolide by methylating the 23S rRNA gene [26].

5.3 Broad Spectrum Control

The L. garvieae strain produces garvicin KS, which is made up of three related peptides. Using an agar diffusion technique, its inhibitory efficacy was first examined on 250 indicator bacteria, 240 of which (19 species) were Gram-positive bacteria were used. With a single exception of three out of 53. S. aureus organisms, every Gram-positive bacterium tested was sensitive (results not shown). The minimum inhibitory concentrations (MICs) of garvicin KS against a representative set of bacteria. Pathogens such as S. aureus, Listeria monocytogenes, and Bacillus cereus vegetative cells were suppressed by garvicin KS. Garvicin KS's impact on spores was not examined [27]. The lactic acid bacteria Lactococcus and Enterococcus strains with MICs ranging from 5 to 80 BU/mL were the most sensitive. A combination containing 10 nM of each of the pure garvicin KS peptides is equivalent to 5 BU/mL. The range of concentrations to inhibit other strains of Gram-positive bacteria was 320–2560 BU/mL. The inhibitory effect of garvicin KS on the growth of A. baumannii, A. iwoffii, and A. calcoaceticus was noteworthy (MIC = 2560 BU/mL). Other Gram-negative bacteria, including P. aeruginosa and E. coli, did not, however, exhibit a reaction to garvicin KS in this experiment [28].

6. Synergistic Approaches in Biocontrol Strategies

Promising methods for attaining efficient and long-lasting crop protection include synergistic techniques that combine phytochemical biopesticides with microbial biocontrol agents. The use of living things or their metabolic byproducts to lessen the effects of plant diseases is sometimes referred to as biological control. The effectiveness of microorganisms acting as biological pest control agents (BCAs), for instance, is greatly impacted by physiological and environmental factors [29] . These processes include competition, antibiosis, and parasitism. Strong insecticidal, fungicidal, nematoidal, and bactericidal properties are displayed by phytochemical biopesticides, which are made from secondary metabolites of plants, such as essential oils, alkaloids, flavonoids, and coumarins that are taken from herbs, spices, or fragrant plants. Compared to traditional chemical pesticides, these natural alternatives are safer for plants, consumers, and the environment [30]. Combining microbial antagonists with biochemicals derived from plants has been shown to have synergistic or additive impacts against a variety of insect pests and phytopathogens in a variety of agricultural systems. Expanding the use of these synergistic biocontrol strategies plants could significantly lessen reliance on artificial agrochemicals and encourage the shift to sustainable plant protection [31].

7.Environmental Impact of Biocontrol Agents.

Microbial biocontrol agents are recognised as environmentally sustainable components of modern pest management programs, in keeping with the goals of eco-friendly agriculture [32]. Commercially available products derived from beneficial bacteria aim to both effectively preserve crops and lessen environmental issues. Phytochemical biopesticides, especially those based on essential oils and plant secondary metabolites, are preferred over conventional agricultural methods because to their short ecological persistence, rapid biodegradability, and minimal environmental impact.rochemicals [33]. By using them, farmers may protect crops while also safeguarding beneficial creatures, minimising soil and water contamination, and fostering ecosystem health. When combined, these bioplant-based solutions provide protection that balances ecological integrity and agricultural output, making them a crucial environmental foundation of integrated pest-management (IPM) systems [34]. Aspects of Ecosystem Health For pest management to be sustainable, biopesticides derived from microorganisms and plants must continue to be compatible with ecosystem balance and biodiversity. By ensuring compatibility, helpful agents are introduced without unintentionally upsetting higher-trophic species or local microbial populations. Certain microbial–phytochemical combinations clearly show synergism; for example, the combination of the citratus (lemongrass) essential oil and Fusarium oxysporum biocontrol agents improves plant resistance and pathogen suppression. However, other combinations, like Fungus Bacillus with essential oils of the aromatic plant Syzygium (clove) as well as Cinnamomum zeylanicum (cinnamon) or Ocimum basilicum oil (basil) may out to be antagonistic. The strong antibacterial components of these oils, particularly eugenol and cinnamonaldehyde, tear down bacterial cell membranes, disrupt ATPase activity, and reduce spore germination in varieties of Bacillus [35]. These substances are the cause of this incompatibility. These effects reduce spore survival and metabolic activity, which reduces the biocontrol efficacy of Bacillus-based formulations. Experiments have demonstrated similar inhibitory effects between Bacillus subtilis bacterium & phenolic-rich essential oils in both in vivo and bioformulation experiments. On the other hand, numerous good encounters have also been reported. Plant-derived compounds can encourage microbial colonisation or metabolic activity, while bacteria like Pseudomonas sp., Bacillus subtilis, and Bacillus velezensis improve the solubilisation & absorption of phytochemical components. This type of positive feedback shows how carefully calibrated mixtures of microorganisms and phytochemicals can maintain rather than disturb ecological balance. The biological underpinnings of compatibility and antagonism must be understood in order to develop next-generation formulations that optimise pest control effectiveness without sacrificing environmental purity [36]. Biodefense and Biodiversity

Numerous microbial species demonstrate strong biocontrol activity in field and horticultural crops via mechanisms such mycoparasitism, induced systemic resistance (ISR), competition, and antibiosis. Broad-spectrum action, environmental safety, and very straightforward production processes are all provided by these mechanisms. Together, microbial and phytochemical biopesticides boost agro ecosystem biodiversity and restore soil microbial stability by lowering reliance on synthetic pesticides. However, as was previously mentioned, commercial expansion still faces economic and legal obstacles, highlighting the necessity of environmentally conscious innovation in developing goods. The ecological impact of crop-protection regimens is decreased when microbial biocontrol and phytochemical formulations are combined, improving field performance. Although phytochemicals, which are naturally occurring plant metabolites that offer defence against infections and insects, are typically extracted from plant tissues, seasonal fluctuations can impact the constancy of their supply and composition. A sustainable and repeatable alternative is offered by plant-tissue-culture technologies, which guarantee the ongoing synthesis of consistent bioactive chemicals for large-scale biopesticide manufacturing [38]. By preserving genetic and chemical integrity and reducing the strain on wild plant resources, this method strengthens the environmental sustainability of phytochemical production. Improved pest management and increased ecosystem resilience are two advantages that agriculture can obtain by incorporating microbiological and phytochemical techniques within carefully regulated frameworks [39].

8. Synergistic Approaches in Biocontrol Strategies

Promising methods for attaining efficient and long-lasting crop protection include synergistic techniques that combine phytochemical biopesticides and microbial biocontrol agents. In general, Biological control is the application of living things or products derived from their metabolic process to lessen the impact of plant diseases. The effectiveness of microorganisms acting are biological control agents, and BCAs, is greatly influenced by physiological and environmental conditions. Among these mechanisms are rivalry, parasitism, and antibiosis. Phytochemical biopesticides have strong insecticidal, like nematoidal, and bactericidal activities [39]. They come from secondary metabolites that are taken from aromatic plants, including essential oils, alkaloids, flavonoids, & coumarins.

herbs, and spices. These natural products are safer than conventional chemical pesticides for crops, consumers, and the environment. It has been demonstrated that plant-derived biochemicals and microbial antagonists have complementary or synergistic effects against a range of insect pests.and phytopathogens in a variety of crop systems. Expanded use of these synergistic biocontrol layers Plants have the potential to significantly lessen reliance on artificial agrochemicals and facilitate the shift to sustainable plant protection.

8.1Combining Microbial and Phytochemical Agents

Now increasingly acknowledged as a comprehensive and all-encompassing framework for the long-term management of plant diseases, integrated pest management, also known as I has experienced remarkable growth. The concepts of sustainability, food safety, and environmental protection are all in line with IPM strategies, which incorporate a variety of ecologically conscious crop protection techniques, such as biological management, host plant resistance, physical and cultural practices, and the prudent use of chemical agents. For IPM to be successful, eco-friendly substitutes must prove to be just as effective as or more effective than synthetic pesticides in order for farmers to adopt them. According to recent research, when used effectively, biocontrol agent (BCA)-based techniques can equal or even outperform traditional chemical controls, furthering the creation of effective and long-lasting crop protection systems.

8.2 Case Studies of Successful Synergies

If phytochemical biopesticides are substances derived from plants that are assessed for their efficacy in protecting crops, biocontrol chemicals (BCAs) are microbes used to reduce or eradicate phytopathogens. Research examining the combined use of these two tactics has repeatedly shown synergistic interactions that improve the suppression of pathogen proliferation and disease progression, leading to higher accuracy than when either agent is used alone. These Several complimentary pathways can account for synergistic outcomes at the molecular level. Numerous antioxidants, flavonoids, and terpenoids produced by the tissues of plants at sublethal amounts are used to be antagonists and signalling molecules by beneficial bacteria and fungi. By encouraging chemotaxis, root-surface stickiness, and biofilm formation, they can enhance the rhizosphere including groups involving Pseudomonas, Bacillus, and Trichoderma. plant colonisation and the pathogen's geographical closeness. Furthermore, several phytochemicals enhance direct antagonism by modifying microbial gene expression and activating clusters of biosynthetic genes involved in the synthesis of antimicrobial agents, fatty acids, volatile organic substances, and cell-wall destroying enzymes. Additionally, a number of phytochemicals stimulate plant defence signalling through the ethylene, salicylic acid, and jasmonic acid pathways; when paired with systemic resistance generated by microbes, this leads to a higher and faster activation of defense-related genes and metabolite. Saponins and other substances that resemble surfactants can further increase the permeability of pathogen membranes, making them more vulnerable to microbial toxins. When combined, these effects produce multi-layered interference with pathogen infection cycles, which helps to explain why single-agent applications are often outperformed by microbial–phytochemical combos(40). Although the outcomes from synergistic formulations are encouraging, their combination use also presents unique formulation-related and ecological issues that need to be carefully managed. Unintended antagonistic interactions can occasionally arise in soil ecosystems due to the dynamic interactions between microbial with phytochemical components and the native microbiota. High levels of phenolic or terpenoid chemicals, for instance, may prevent beneficial bacteria like Bacillus subtilis or Trichoderma harzianum from germination of spores or from enzymatically interacting with one another [41]. In a similar vein, some essential oils have the ability to disrupt the overall composition of the soil microbial community by altering nutrient cycling, root-microbe signalling, and selectively suppressing sensitive taxa. To lessen these worries, dosage consistency and compatibility are crucial. The identification for threshold concentrations that improve biocontrol efficacy without compromising microbial survivability or soil functions is made easier by laboratory screening and microscopic studies.

Co-formulated encapsulation techniques or sequential application strategies (e.g., staggered bacterial & phytochemical delivery) may be devised to prevent direct antagonistic contact and provide stability in field settings.Additionally, for regulatory approval and practical implementation, tank-mix compatibility testing and unambiguous labelling standards like those for chemical-biological mixtures—are crucial. In the end, rigorous formulation design, risk assessment, and validation on the ground are critical to the success of combined biocontrol techniques, ensuring that possible environmental trade-offs are outweighed by synergistic advantages. When the two components have different modes of action or atmospheric persistence, the combined biocontrol techniques' efficacy and dependability frequently rise. A variety of biocontrol strategies, such as parasitism, competition, the generation of bioactive metabolites, and the induction of plant resistance, is employed by several microorganisms to offer strong and long-lasting pathogen suppression. These various mechanisms and materials have been the subject of numerous investigations to assess their potential as creative, environmentally sustainable disease management solutions. Even though chemical fungicides have come a long way since they were first widely used in the 1940s, their broad use creates serious issues with human health, food safety, and environmental sustainability. Numerous artificial fungicides contribute to ozone depletion and have toxic, Mutagenic carcinogenic, or teratogenic effects. Additionally, the buildup of chemical residues in food items might cause consumers to have acute or chronic physiological issues. Effective, long-lasting, and ecologically friendly substitutes that protect ecological integrity and human health are thus desperately needed. Living microorganisms, herbal extracts, oily substances, and their bioactive constituents are examples of biopesticides that have shown promise as alternatives thus far. These naturally occurring substances provide novel, secure, and transient crop protection solutions by mimicking the biochemical defence systems of plants and other organisms [42].

9. Factors influencing Synergism

Shigella is the class of plants includes gram- positive, facultative, air-deprived, non-spore-making, static, rod-shaped microorganisms that cause shigellosis. The therapeutic importance of different Shigella species varies geographically.The most common Shigella species in industrialized and developing nations, respectively, are the two genera Shigella flexneri and Shigella sonnei. Shigella boydii accounts for around 4% of all shigellosis cases worldwide, while Shigella dysenteriae is primarily found in South Asia along with sub-Saharan Africa. Shigellosis is a serious international health issue that kills over 100,000 people annually [43]. Shigella infections can be transmitted between individuals or through tainted food or water. When an infected person is ill or for one to two weeks following, the pathogenic germs are typically discovered in their diarrheal feces. The illness's symptoms include fever, nausea, vomiting, diarrhea that occasionally contains blood, and cramping in the abdomen. Shigellosis has an effect on people's health as well as the economy of both individuals and countries. Every year, significant financial losses are reported as a result of clinical treatment expenses and missed employment. Shigellosis is mostly treated with medicines, including ceftriaxone, azithromycin, ciprofloxacin, ofloxacin, and norfloxacin. But at the moment, this treatment strategy is dubious. It may cause bacteria to become resistant to drugs, which can then spread to other harmful bacteria in the environment and to humans (Davidson & Harrison). Because it restricts treatment choices, the rising incidence of antibiotic resistance in bacteria Shigella is also concerning. Since using antibiotics to treat shigellosis has become less successful and risky, preventing Shigella contamination in food and drink has drawn more attention as a substitute method of disease control [44]. To avoid Shigella infection, some food preservation techniques, like heat treatments and the use of artificial preservatives, can be employed. However, these systems can have unfavorable effects and go against consumer and food industry needs for food items that are fresher, more natural-tasting, and additive-free while still preserving microbiological safety (Gould). Using naturally occurring substances that are generally accepted as safe (GRAS) to stop Shigella could be one way to meet this requirement in food preservation.

10. Bio insecticide Synergy

The commercial bioinsecticide segment is dominated by microorganisms insecticides are dominant, which encompass both products that originate from surviving microorganisms that have been proven pathogenic in pest insects (viruses and fungi) as well as compounds that act by producing specific insect pathogenic organisms (for example, bacteria that are part of the Bacillus thuringiensis (Bt) complex). Avermectins, which are produced by fermenting the soil bacterium Streptomyces avermitilis avermitilis spinosa from the soil actinomycete, are likewise included in the latter group. In order to create genetically modified crops, it has been common practice to stack different Cry genes that produce Bt endotoxins. However, combinations of Bt chemicals that act as active ingredients in externally applied bioinsecticides are much less common, and the synergy between such toxins has not been well documented.It may seem obvious that an insecticidal toxin, whether natural or synthetic, would oppose entomopathogenic microorganisms that kill insects through rapid reproduction within a host insect's body because the toxin could stop the pathogen's innocula from being produced and spreading by killing the insect too soon. On the contrary, there are more recent instances of entomopathogenic fungal organisms and botanical insecticides working together, or at least not antagonistically. revealed that the thrips were effectively suppressed by a combination of the botanical pesticide matrine (a quinolizine alkaloid) and the entomopathogenic fungus Akanthomyces. These findings attenuate. Despite the fact that the alkaloid suppressed fungi germination and colony formation at greater concentrations, Megalurothrips usitatus, a cowpea pest in China, was nevertheless affected. The same authors previously conducted laboratory and greenhouse tests to assess the effectiveness of the fungus Beauveria brongniartii, the bacteria matrine, and combinations of these against tobacco cutworm larvae (Spodoptera litura). The fungus's germination and colony formation were not impeded by matrine, and the cutworm's mortality in both tests was greatly increased when the fungus and botanical are combined. This fungus shares a mechanism of action with matrine by producing a peptide metabolite called bassianaolide that inhibits the synthesis of acetylcholinesterase. The results that extend from the greenhouse experiments (referred to as "field conditions" in the paper) were very promising; larval death from individual treatments varied from 30 to 52%, while mortality from combination treatments ranged from 80 to 89%. Pyrethrum, the most popular botanical insecticide, and the fungus anisopliae fungus Metarhizium were found to have a combined effect on the bean caterpillar, Aphis fabae, in a laboratory study [45]. The combined treatment increased aphid mortality and significantly shortened the time it took for visible fungal growth to appear on the host insects' protective layer by up to 84 hours. Botanical insecticides have historically been used in combination with extracts from multiple plants, typically from different plant families, as have smallholder farmers' present "home-made" bioinsecticides. The current unregulated or informal mixes may eventually help broaden the range of action against pest insects, but they may also profit from the synergy between the extracts of their constituents Xu et al. assessed the toxicity of two quinolizidine-derived alkaloids from Sophora flavescens, matrine and oxymatrine, both separately and in binary combinations, as well as a tertiary combination that included 1,8-cineole, a significant component of the essential oil of Eucalyptus globulus and several other plants, to Plutella xylostella larvae. In both laboratory and greenhouse trials, they found that the tertiary mixture containing 1,8-cineole was significantly synergistic as a bioinsecticide, and that an 8:2 matrine/oxymatrine ratio was more lethal than either constituent alone. When same mixes were evaluated against the twospotted tarantula mite Tetranychus urticae, they found a similar occurrence [46]. Any specific plant's essential oil can be a complicated blend of several mono- and sesquiterpenoids; and related chemicals. Early research on the toxicity of oregano (Rosmarinus officinale) oil to moths revealed that the insecticidal action could not be attributed to a single component. According to a thorough investigation, at least 90% of the bioactivity detected in the cauliflower looper Trichoplusia ni may be explained by the synergistic action of 2 oil constituents: camphor and 1,8-cineole. Later research found that essential oil terpenes, both those separated from several oils and those found inside a single oil, can work in concert a lot of the time. In addition, 1,8-cineole seems to enhance camphor's toxicity by making it easier for the latter to pass through insect integument. The synergy of the two main components of thyme (Thymus vulgaris) essential oil, p-cymene and thymol, showed a similar impact. In this instance, the latter molecule enhanced thymol penetration in adult household insects, Musca domestica, hence synergizing the toxicity of the former. It has also been observed that a third-party mixture of the aromatic compounds that include carvacrol, eugenol, and thymol in bed bugs exhibits insecticidal synergy through increased cuticular penetration. lectularius Cimex Botanical insecticides have historically been used in combination with extracts from multiple plants, typically from different plant families, as have smallholder farmers' present "home-made" bioinsecticides. The current unregulated or informal mixes may eventually help broaden the range of action against pests such as insects, but they may also profit from the synergy between the extracts of their constituents. Combinations of various plant extracts and possibly essential oils are also found in some commercial botanical pesticides. However, scientific examination of these kinds of synergy has only recently begun. In adult yellow fever mosquitoes (A. aegypti), Norris and Bloomquist investigated the possible synergistic activity of various plant essential oils with pyrethrins which serve as predators and knockdown agents however, the ideal matrine/oxymatrine ratio.

Any specific plant's essential oil can be a complicated blend of several mono- and sesquiterpenoids together with associated chemicals. Early research on the toxicity of rosemary's (Rosmarinus officinale) leaves oil to insects revealed that the insecticidal action could not be attributed to a single component. According to a thorough investigation, at least 90% of the bioactivity detected in the cauliflower looper Trichoplusia ni may be explained by the synergistic action of 2 oil constituents [47].

11. Biological pest Control

By employing trap agricultural produce, releasing biocontrol agents, creating habitat for beneficial creatures, or using biopesticides—pesticides derived from natural sources such microorganisms, plants, animal tissue, or minerals—organic farmers can manage pests. Living creatures that humans introduce or support with the goal of harming invertebrate pests are known as biocontrol (biological control) agents. Because biocontrol agents target pests, they are sometimes referred to as "enemies." Predators, parasitoids, parasites, and pest infections are examples of biocontrol agents. Farmers can offer "SNAP"—shelter, nectar, alternative prey, and pollen—to maintain a robust and stable colony of biocontrol agents. Untilled regions, mulch, perennial plantings, hedgerows, or wild areas are examples of places that organisms require shelter throughout the year, even the winter.Growers can use insectary strips, which are flowering plants with various floral traits and blooming times, to supply pollen and nectar. Higher crop yields may result from pollinator habitat provided by wild areas and flowered strips. By cultivating trap crops—plants that draw pests—farmers can concentrate pests. By tilling or mowing the trap crops or using a botanical insecticide, this can deflect bugs from agricultural produce and make it simpler to eradicate pests. Invertebrates, which include pest parasitoids and predators, help manage pests on organic farms. Compared to non-organic farms, organic farms often harbour a higher variety and quantity of these species. Farmers are crucial because they provide habitats that supports these biological pesticides and make sure crops are healthy, even while wasps, beetles, and other insects destroy the pests. Producers may use biopesticides or release organisms to battle pests if these preventative measures prove insufficient. Invertebrates, which include pest parasitoids and predators, help manage pests on organic farms. Compared to non-organic farms, organic farms often harbour a higher variety and quantity of these species. Farmers are crucial because they provide habitat for these biocontrol agents and make sure crops are healthy, even while wasps, beetles, and other insects destroy the pests. Producers may use biopesticides or release organisms to battle pests if these preventative measures prove insufficient. biopesticides. The type of pest and degree management pest danger, the system for cultivation (field crops, market garden or greenhouse), and the operator's preferences all influence the approach selection [48]. Insecticidal or repellant chemicals are found in many plants that serve as habitat for parasitoids and predators. Operators can manufacture crude extracts from the foliage of various plants, such as clove basil, buckwheat, coriander, and oregano, in addition to intercropping them. When these biopesticides are sprayed on crops, many plants that serve as habitat for parasitoids and predators also contain insecticidal or repellant chemicals. Operators can manufacture basic solutions from the foliage of various plants, such as clove basil, buckwheat, coriander, and oregano, in besides intercropping them. Many organic farmers used Dispel or another commercial item containing bacteria in the soil (Bacillus thuringiensis var. kurstaki) to control caterpillars in brassicas. Regrettably, a lot of pests have become resistant to Bt. OSC researchers are investigating alternatives and have discovered that applications of the fungus Beauveria bassiana (BotaniGard) and specific viruses can control imported cabbageworms, cabbage loopers, and diamondback moths24.

12. Future Perspective and Advancements

Semiochemicals and biocontrol agents interact in a variety of ways. While there is a wealth of information about fragrances and plant-based semiochemicals for many insect pests, little is known about how semiochemicals interact with biocontrol agents, particularly microbials. In a similar vein, we still need to learn more about the origins and development of semiochemicals in relation to biocontrol agents. To further understand this tri-trophic relationship, it is necessary to determine the whole chemical profiles of the plants that host natural enemies as well as the genotype of the species. The foraging efficiency of insect biocontrol agents can be improved by the ideal release rates of chemical semiconductors.To enhance the safeguarding use of biological fertilisers, more research into non-host plants for potential usage as intercrops and trap crops is required. Future biological control initiatives may heavily rely on the determination of kairomones from insect pest whole-body washes. To include additional kairomones with biocontrol agents, it is necessary to investigate the primary source signs of compounds in both laboratory and field research. This will undoubtedly be aided by a better knowledge of the genes that produce semiochemicals. Further field research concentrating on appropriate dosage and economic assessments is also required.Connecting identified chemical ingredients with microbes biocontrol agents should be the main goal of studies of insects as pests for which the chemical makeup of different semiochemicals is already known. Since a number of additional ecological elements are important in these interactions, the most common tri-trophic interaction has recently been reclassified to serve as multi-trophic interaction. More research on how different BCAs interact and are compatible with one another might guarantee higher success. Further research is required to determine how symbionts (in insects) and endophytes (in plants) affect BCAs and whether it is possible to control their release of semiochemicals.It is becoming more common to use recognised semiochemicals to draw in natural adversaries in the field. However, details regarding the exact identity, quantity, application technique, and release rate of appealing chemicals are still frequently lacking. In addition to identifying semiochemicals, applying selected components to attract natural enemies requires a careful and exacting method in order to create an effective biological control program. Semiochemicals manipulate natural enemy populations through chemical application, habitat modification, host plant modification, and parasitoid manipulation. Building an appropriate ecological infrastructure includes both recruiting and protecting natural enemies. For natural enemies, successful implementation requires choosing suitable HIPVs, floral scents, and host-associated cues, testing them in lab and field settings, combining themselves with other biological pest management techniques, and, lastly, routinely monitoring the activity, density, and parasitism rate of natural enemies as well as the host's density, damage, and yields. Additionally, the immediate implementation of semiochemicals in the field entails the use of synthetic compounds either singly or in combination through slow-release dispensers to act directly on natural enemies, or the use of synthetic compounds to trigger a plant's chemical defence to draw in natural enemies.The "attract and reward" method, which uses food sources as traps to keep natural adversaries, is also employed. Laboratory bioassays, semiochemical-baited trap optimisation, trap setup and calibration, and assessing the degree of attraction under field conditions are all part of the procedure. Auto-dissemination is emerging as a key field of research for the efficient and economical application associated with these microbiological biological control agents, particularly in the context of "lure and kill" systems. A successful pest management system must include trap placement, equipment, and an application plan for auto dispersion [49]. The largest obstacle to integrating semiochemicals with microbes is luring and infecting techniques and device optimisation. Although there have been more research utilising semiochemicals in the field in recent years, there is still a dearth of data. Given these problems, breeding as well genetic engineering plants to create and release particular volatiles could be an option. Rising food demand, a shortage of arable land, and growing pesticide and pathogen pressure are just a few of the growing issues facing modern agriculture. There is a pressing demand for environmentally friendly substitutes since phytopathogen resistance has decreased the efficacy of synthetic agrochemicals. Therefore, it is now crucial to create innovative bio-based insecticides sustainably in order to safeguard both yield and environmental quality.Large-scale commercialisation of microbial biocontrol products (MBCAs) is limited by manufacturing, and composition, and field performance challenges, despite the fact that MBCAs provide sustainable pest control [50]. However, because to their strong antimicrobial activity and minimal ecological impact, phytochemical biopesticides are important synergistic partners. Thus, creating synergistic MBCA–phytochemical combinations presents a viable and creative approach to robust, long-term crop protection. Plant-derived substances from essential oils, leaves, stems, or seeds are known as phytochemical biopesticides, and they are less harmful and more effective than synthetic pesticides. However, widespread use is still hampered by production costs, market acceptance, and strict regulations. The combined actions of phytochemical biopesticides and microbial biocontrol agents can increase efficacy while lowering environmental load. Therefore, supporting integrated biocontrol techniques and encouraging regulatory flexibility could increase uptake and promote sustainable agriculture. The next stage in the development of BCA is represented by microbial consortia that include complementary varieties or strains with distinct antagonistic mechanisms. Despite laboratory studies demonstrating improved pathogen suppression, few multi-strain compositions have yet been successfully commercialised. Developing reliable, durable formulations remains a significant challenge. It will be crucial to further optimise strain reliability, carrier materials, & field distribution methods in order to fully exploit the abilities of collaboration-based biocontrol and provide an environmentally sound future for the preservation of plants [50].

13.Conclusion

In order to reduce reliance on synthetic agrochemicals and increase plant resistance to a variety of biotic stressors, sustainable crop protection includes an extensive array of cutting-edge technological techniques. By lowering production, quality, and environmental stability, these stressors—which come from diseases, pests, and pathogens—continue to pose a danger to the world's food security. Two main types of biopesticides have become essential to sustainable farming in this changing agricultural environment: phytochemical biopesticides and microbial biocontrol agents (MBCAs). Both are generated from naturally existing chemical signals that serve as the basis for environmentally friendly crop security mechanisms by mediating inter-organismal communication. By combining the chemical variety of plant metabolites with the precision of microbial antagonism, these two biological methods provide a synergistic platform.

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