*Review Article*

Integrated Bio-Approaches for Tuber Crops Protection against key-pests: A Sustainable Review

ABSTRACT

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| The use of bio-pesticides and bio-control agents must be promoted in agriculture as they have no such toxic effect on the environment or the population. Application of organic pesticides, also known as biopesticides, is eco-friendlier and more sustainable, and has become essential because of the dangers associated with synthetic pesticides. Emerging tools, such as semiochemicals, plant-derived protective agents (PIPs), along with substances derived from plants and those of microbial origin, are increasingly contributing to pest management. This approach is complemented by advances in genetics of plants and animals, management through biological means, agricultural methods and the development of new synthetic options. In contrast to synthetic pesticide, microbial pesticides targets specific organisms, and are easily obtainable and have no lasting effect on the natural resources. In this review we investigate the various kind of bio-pesticides and bio-control agents that are used in tuber against its key pest without causing any harm to the environment. |

*Keywords: Tuber crops, Bio-Approaches, Key-pests, Bio-pesticides, Bio-control agents*

1. INTRODUCTION

Tuber crops ranks as the third most significant agricultural crops following cereals, grains and legumes. Tropical tuber crops like cassava, sweet potato, aroids, yam and elephant foot yam are essential for global food stability and economic progression, especially in developing countries. As reported by the Food and Agriculture Organization (FAO), these crops cover around 52.19 million hectares (mha) of land worldwide, producing approximately 523.19 million tonnes (MT) each year [18]. Currently, the cultivation of tuber crops, except potato, is predominant in the peninsular and North-eastern regions.

They are distinctive because of their natural characteristics, which include their high dry matter production, ability to endure the effects of climate change, and ability to provide millions of people in tropical and subtropical nations with food security [61]. The trade dynamics surrounding tuber crops highlight their importance within the global agricultural sector. For instance, India stands out as a prominent exporter of tuber crops like cassava, sweet potatoes and yams, serving a variety of international markets. In recent times, the farming of tuber crops has gained more focus because of their adaptability, nutritional benefits, and ability to thrive in different environmental conditions. In addition to serving as a main food source, tropical tuber crops are well-known for their healing qualities. Numerous varieties are utilized in the formulation of Ayurveda and Unani remedies for various ailments. They are also employed as stimulants, tonics, carminatives, diuretics, and expectorants [58]. Tuber crops exhibit the greatest rate of dry matter production and are regarded as the most effective converters of solar energy.

However, insect pests and diseases present major difficulties in the cultivation of tuber crops, leading to considerable yield reductions and economic consequences in different areas. The papaya mealybug (*Paracoccus marginatus*), for instance has become a major pest of cassava in the recent years [35], similarly the sweet potato vine borer (*Omphisa anastomosalis*) is an emerging pest that grow and feed within the vines, particularly in the crowns, leading to a notable decrease in yield of sweet potato [48]. Two major challenges need to be addressed for sustainable organic potato production: efficient controlling of the phytosanitary state of the agroecosystem and ensuring adequate mineral nutrition of potatoes [26]. Both of these elements are subjected to regulatory restrictions, while outlawing the application of most synthetic pesticides, also forbid the use of artificial fertilizers, particularly nitrogen fertilizers. Therefore, to lower the population density of these phytopathogenic species it is crucial to choose safe and effective microbiological pesticides.

The green revolution technology has been characterized by excessive use of high yielding varieties, chemical fertilizers, pesticides and irrigation water [36]. The Green Revolution has greatly increased agricultural output, but the significant dependence on chemical fertilizers and pesticides has introduced various environmental and sustainability issues. Nonetheless, this overuse of synthetic pesticides, intended to enhance their effectiveness, poses substantial risks to human health and other organisms. To protect the nature and promote sustainable crop production practices, a comprehensive approach is crucial in today's context. These innovative pest control strategies signify a revolutionary method of managing pests, harmonizing technological advancement with environmental conservation and agricultural yield. The aim of environmentally friendly techniques is to manage pests through the utilization of natural resources and practices, such as bio-pesticides derived from plants and biological control agents.

Bio-pesticides serves as an eco-friendly alternative in relation to chemical pesticides which are sourced from organic origin such as plants, micro-organisms and insects. These are comparatively less toxic and cause lower environmental impact and can be beneficial against insecticide-resistant pests. It also plays an important role in conservation of ecological balance in the environment [76]. Global bio-pesticide production exceeds 3,000 tons annually and is growing quickly. Bio- pesticides can be divided into three broad classes namely: microbial bio-pesticides, bio-chemical pesticides and plant-incorporated protectants. The application of botanicals/bio-chemicals has proved to be best for controlling shoot borers and mites in potato and other tuber crops. These bio pesticides and botanicals are so far safer for both the environment and the applicator can be recommended as they are effective against insect pest without any fear of residues in tubers.

Biocontrol agents seek to create sustainable and eco-friendly options to replace conventional chemical pesticides in the management of plant diseases. Biological control utilizes advantageous organisms, their genetic material, and/or their by-products, like metabolites, which mitigate the harmful effects of plant pathogens and encourage beneficial reactions from the plant [33]. Several commercial biocontrol agents have been authorized at both national and international levels, utilizing various fungal and bacterial antagonists. Biological control manages disease suppression through a range of intricate mechanisms that work together to safeguard plant health. The primary mechanisms for disease suppression encompass antibiosis, competition, mycoparasitism, degradation of cell walls, induced resistance, promotion of plant growth and the ability to colonize the rhizosphere. The most commonly utilized bio-agent to date is *Pseudomonas*, which exhibits exceptional versatility in combating disease-causing microorganisms.

2. BIOPESTICIDES: AN ECOFRIENDLY ALTERNATIVE

Biopesticides are effective and safer means of controlling pests, they have a mild effect on the environment compared to their synthetic counterpart, and they are specific in their target, hence preventing bioaccumulation [68, 28]. Their unique properties contribute to more sustainable agricultural practices while minimizing environmental impact. Biopesticides are made from natural substances, such as plants, microbes, and nanoparticles of biological origin, thus, making them a sustainable means of pest control [28]. Biopesticides are completely harmless to both humans and the environment, and they have minimal impact on human health and ecosystems compared to traditional pesticides [9]. As a result, incorporating bio-pesticides into integrated pest management (IPM) initiatives provides an advanced and sustainable method for handling agricultural pests while preserving crop yields. Biopesticides are essential for safeguarding crops, frequently utilized alongside other options such as biochemical pesticides as part of a bio-intensive integrated pest management strategy [65]. Plant-based bioactive substances offer a sustainable alternative that merits investigation. Numerous studies have shown that plant extracts, which hold complex combinations of these substances, demonstrate impressive qualities like insecticidal, repellent, ovicidal, antifeedant, and anti-oviposition effects. Herbs like basil are rich in essential oils that not only exhibit significant vapor toxicity against adult pests but also serve as effective ovicides and larvicides, effectively suppressing reproduction [38].

**2.1 BIOPESTICIDES FORMULATIONS**

Biopesticides are created in a manner similar to synthetic pesticides, allowing farmers to use the same application equipment. This thoughtful design facilitates a smooth shift towards more sustainable practices while maintaining operational efficiency [39]. Biopesticides are inherently derived from biological entities, and is essential to preserve their sustainability throughout the formulation and preservation phases. These organisms should consistently switch from their resting state to active state at the point of application to maximize efficacy [65]. The end product is strictly formulated by combining the microbial component with a range of well-selected carriers and adjuvants. This potent mixture ensures strong protection against environmental factors, provides accurate control of release rates, increases bioactivity, and optimizes storage stability. In order to attain the major functions of advanced biopesticide formulations, a number of factors need to be taken into consideration. These involve making the product easy to handle and apply, stabilizing the microbial agents during storage and distribution, safeguarding the bioagents from unfavorable environmental factors, and enhancing their performance by maximizing the exposure and interaction with the subjected pests. In order to guarantee these goals are attained, biopesticides can be formulated in different manners [47]. The effectiveness of biopesticide formulations, whether dry or liquid, depends on the strategic application of active ingredients blended with necessary additives. By adding stabilizers, synergists, spreads, stickers, surfactants, coloring agents, anti-freezing agents, extra nutrients, dispersants, and melting agents, these formulations can reach their optimal performance in efficient pest control [68,7]. Biopesticides are generally formulated as liquid and dry formulations.

**2.1.1 Liquid Formulations**

Liquid formulations are following types:

**Emulsions:**They are designed to blend with water, categorizing them as either oil in water (O/W) or water in oil (W/O). It is imperative to select the right emulsifiers; this choice is critical for maintaining stability and preventing issues. A decisive approach in this selection is essential for achieving optimal performance. In a water-in-oil emulsion, the oil in the external phase significantly reduces losses due to evaporation and spray drift, ensuring greater stability and efficiency in the formulation [68,39].

**Suspension Concentrate (SC):** It is a popular type of formulation because of safety to operator and environment [6,75]. This state-of-the-art formulation mixes finely milled solid active components with water for maximum efficacy. It is crucial to agitate the mixture prior to application in order to have even distribution since the solid particles don't dissolve. With a particle size of only 1 to 10 micrometers (µm), these minute particles increase penetration of active components into plant tissues, resulting in superior bio efficacy and exceptional results.

**Suspo-emulsion (SE):** A suspo-emulsion (SE) is a formulation containing both solid and liquid active constituents dispersed in an aqueous phase.This formulation expertly combines emulsion and suspension concentrate to guarantee superior stability and performance. By integrating a homogeneous emulsion with a well-dispersed particle suspension, we deliver a high-quality product that reliably maintains its integrity over time. In addition, it is necessary to be carried out using storage stability resting [7].

**Oil Dispersion (OD):** The formulation product is created in a similar way as that of suspension concentrate. Instability problems could be avoided by proper selection of inert ingredients [76].

**Capsule Suspension (CS):** The active components are formulated in a micro-encapsulated suspension that requires water dilution before use. Gelatin, starch, and cellulose capsules shield bioagents from extreme conditions. Interfacial polymerization is the main technique for developing smaller, effective formulations, especially for fungal biopesticides [60].

**Ultra-Low Volume Liquid (ULV):** Formulations are not diluted in water prior and contain concentrated active ingredients. They are easy to transport and can include a suspended biocontrol agent as the active ingredient [75].

**2.1.2 Dry Formulations**

Dry formulations (Figure 1) can be used as direct application and these are following types:

**Dustable Powders (DP):** Formulations of dust consist of 10% active ingredients, obtained by adsorbing them onto finely milled mineral powders such as talc and clay (50-100 microns). Inert ingredients are UV stabilizers, adsorption-enhancing adhesives, and anti-caking agents to ensure flow [39].

**Granules:** The level of active ingredients in granules is generally 3% to 20%. Active ingredients can coat the surface of the granules or become deposited into their matrix, enhancing efficacy. To regulate the rate at which these active substances are released after application, granules can be covered with polymers or resins. Granules are mainly used for controlling soil-infesting insects, weeds, and nematodes, and enable efficient absorption by plant roots. Granules having coarse particle size usually fall within the range 100-600 microns and are made of materials like kaolin, silica, starch, polymers, groundnut plant residue, and dry fertilizers [39,73]. Some granules release their active ingredients when they come into contact with soil moisture.

**Seed Dresseing (SD):** One form of biopesticide preparation is prepared through the combination of an active substance with a powder carrier and inert materials to promote the adherence of the final-product to seed coats. Seed dress powders are applicable by the rolling process of the seeds with the product, causing the product to comply with them. The powders also contain colorants, i.e., red pigments, which act as a marker of safety for seeds treated with these [75].

**Wettable Powders (WP):** Wettable powders (WPs) are dry formulations that have been ground into a fine consistency and suspended in water before use. They are developed by mixing active ingredients with synergists, surfactants, and non-active fillers. Because of their grubbiness, rigorous safety precautions are necessary to guard manufacturers and users when applying them since inhaling the dust may cause severe health complications. In addition, wettable powders are of long shelf life, easily miscible with water, and are usable with standard equipment for spraying [68,7].

**Water Dispersible Granules (WDG):** Water-dispersible granules are specially constructed to suspend in water, conclusively overcoming the drawbacks of conventional wettable powders (WPs). They are totally dust-free, ensuring a cleaner application, and they provide outstanding storage stability [7,39].

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**Figure 1: Different types of dry formulations**

*(S. Borah and A.K. Pandav, 2025)*

**2.2 Application Methods of BIOPESTICIDES FORMULATIONS**

The efficacious management of insect-pest can be achieved through the careful selection of application techniques, as well as by determining the appropriate timing and frequency of biopesticides applications. Here are several techniques for application of biopesticides:

**Seed Treatment:** It is one of the best methods to use biopesticides is seed treatment, which is the most effective method used. The process entails the use of powder formulations about 5-10 ml/kg seed through tumbling the seeds with the product, which is specially designed to stick to the seeds. This method not only increases the protection of the seeds but also ensures healthier growth results [20,75].

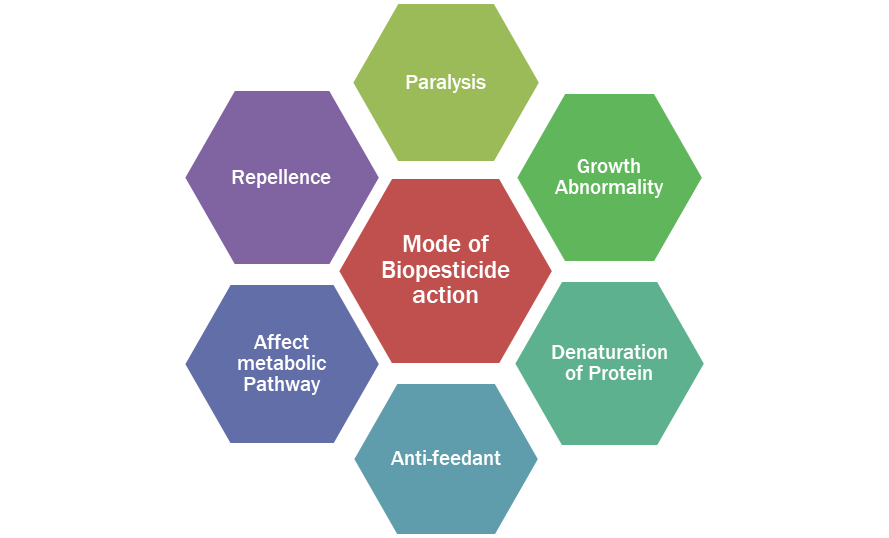
**Foliar Application:** Foliar application is very effective in directly applying biopesticides on the leaf surfaces as sprays. It has proven highly beneficial, for example, in applying Bacillus subtilis on bean leaves that significantly reduce the incidence of bean rust disease from *Uromyces* *phaseoli*. Foliar application (15-20 g/L of water) aids us in protecting crops more effectively and supporting healthier cropping practices.

**Seedling Dipping:** Seedling dipping includes immersing the roots of seedlings in a suspension of biopesticides (5 ml/l water) for several minutes or hours before transplanting. For instance, *Trichoderma* spp. can be used in this method.

**2.3 Mode of Action (Biopesticides)**

The efficacy of biopesticides in pest management is attributed to their diverse modes of action that disrupt gut function, regulate growth and affect the metabolic pathway. The mechanism of Bio-pesticide is followed by denaturing protein synthesis, affecting the metabolic pathway and paralysis, repellency, releasing toxins that affect the pest cellular structure and anti-feedants (bioactive compounds). The mode of action of biopesticides are mentioned in figure 2.

The different modes of action that different classes of microorganism’s use vary. The most common mode of action is Hyper-parasitism. While some antagonists target the sclerotia or mycelium of the fungal pathogen, others kill the pathogen or its propagules. A single pathogen could be attacked by a number of biocontrol agents [19]. *Pasteuria penetrans* is one such example that specifically parasitizes the root knot nematode of *Meloidogyne* sp. Certain hyperparasites, especially species like Trichoderma, produce enzymes that break down cell walls, including chitinase, β-1,3 glucanases, proteases, and cellulose.

** Figure 2: Mode of Bio-pesticide Action**

*(S. Borah and A.K. Pandav, 2025)*

**2.4 Type of Bio-Pesticides**

Three primary categories of bio-pesticides exist: microbial pesticides, bio-chemical pesticides and plant-incorporated protectants (PIPs). A single pathogen could be attacked by a number of biocontrol agents [19].

**2.4.1 Microbial Biopesticides**

Microbial pesticides are derived from micro-organisms, such as bacteria, fungi, viruses and protozoa that are pathogenic to specific insect pests [13]. These biological agents are derived from various micro-organisms:

**Bacteria:** The bacteria that are used as biopesticides can be divided into four categories: crystalliferous spore formers; *Bacillus thuringiensis*, obligate pathogens; *Bacillus popilliae*, potential pathogens; *Serratia marcesens* and facultative pathogens; *Pseudomonas aeruginosa* [52]. Among these, the spore-forming bacteria has become most popular. *Bacillus thuringiensis* (Bt) stands out as an exceptional bacterial pesticide, renowned for its effectiveness and boasting a remarkable track record in commercial application. First discovered in the early 20th century and commercially introduced in 1938 in France, Bt has become a cornerstone of biological pest control. During the sporulation phase, *Bacillus thuringinesis* (Bt) undergoes a unique process of producing insecticidal proteins called delta-endotoxins or Cry proteins. Cry proteins are insecticidal proteins that cause insect death through a sophisticated mechanism targeting the midgut epithelium.

*Bacillus thuringiensis* is used to reduce pest infestation in plants, such as cabbage and potato, and is capable of controlling lepidopterans in different plants [17,70]. Subspecies of *B. thuringiensis* that employed as biopesticides includes *B*. *thuringiensis tenebrionis* (Colorado potato beetle and elm leaf beetle larvae), *B*. *thuringiensis kurstaki* (caterpillars), *B*. *thuringiensis israelensis* (mosquito, black fly and fungus gnat larvae) and *B*. *thuringiensis aizawai* (wax moth larvae and various caterpillars, especially the diamondback moth caterpillar) [52]. In addition to their beneficial effects, commercially available Bt have some disadvantages, such as low environmental awareness and sensitivity, short activity duration, slow lethal rate, and rapid deactivation when exposed to light. Microbial pesticides' short lifespan and environmental sensitivity are the main obstacles to their use, which lowers awareness and usage [15].

**Fungi:** The diversity of fungi suggest that they account for more than 4% of the global fungal diversity which represents a significant ecological component in invertebrate interactions. When spores or conidia encounter the host's cuticle, they inevitably begin to germinate, setting in motion the critical process of infection. Through a combination of enzymatic and mechanical action, the fungus infiltrates into the host body enabling the mycelium to thrive and develop within, resulting in the production of various types of conidia or spores that colonize the host [63]. During its vegetative growth, the fungi releases a variety of biochemical compound which promotes its growth, acts a virulence factors and generates toxic substances. The new spores or conidia produce will ensure environmental spread by enabling new infection cycle. These biochemical and mechanical actions progressively weaken the host and letting it die before the spore production. First conidium or spore germination initiates the infection and typically necessitates particular environmental factors (temperature, relative humidity).

The fungi species *Trichoderma* has shown remarkable potential in combating the detrimental effects of soil fungi that lead to root rot in chickpeas, black gram, green gram, and groundnuts [70]. Similarly, the application of *Beauveria* *bassiana* and sublethal concentration of insecticides have been reported in the management of potato beetle (*Leptinotarsa* *decemlineata*). Entomopathogenic fungi can be effectively utilized by applying in the form of conidia or mycelium that produces spores after application [41]. These fungal entomopathogens offer a promising alternative for managing insecticide-resistant pests.

**Viruses:** Numerous viruses that specifically target and eliminate various insect species are collectively known as entomopathogenic viruses [61]. Among them, the Baculoviridae family stands out as the leading group of viral pathogens affecting arthropods [56]. Baculoviruses have been isolated from an impressive 700 species of arthropods, making them some of the most promising candidates for effective biological control of insect populations [21]. They have been isolated from 700 species of arthropods and include the most promising viruses for insect biological control [40]. While the world of insect viruses is diverse, only a select few are frequently encountered in insect populations, including baculovirus, cypovirus, entomopoxvirus, and iridovirus. [42].

**Protozoa:** Entomopathogenic protozoans, also known as micro-sporidians, are a very broad category of attacking invertebrates which include grasshoppers, rangeland locusts, and many types of insects [43]. They are often slow-acting, host-specific, and cause chronic infections that generally weaken the host. The infectious stage of the protozoan is the spore formation, which must be consumed by the insect host in order to be pathogenic. The host becomes infected when the spore germinates in the midgut and releases sporoplasm, which invades the target cells. Due to the overabundance of microbial control agents, the infection causes the insect host's feeding, vigor, fecundity, and longevity to decrease.

Only a few species have proven effective; for example, *Vairimorpha* *necatrix* has significant commercial potential against caterpillar pests, whereas *Nosema* locust's usefulness as a grasshopper biocontrol agent is still reasonable. Microbial pesticides are applied to the environment through different techniques, such as emulsion, electro spraying system, fluidized bed, spray drying, extrusion, lyophilization, spray cooling, and coacervation [32]. The major categories of microbes used as biopesticides include bacteria genera, *Chromobacterium*, *Pseudomonas* and *Yersinia*, fungal genera *Beauveria, Paecilomyces, Verticillium, Hirsutella, Metarhizium* and *Lecanicillium*, and nematodes belonging to the genera *Steinernema* and *Heterorhabditis* [31,28,12].

**Table 1. Microbial bio-pesticide and their targeted insect pest of tuber crops**

|  |  |  |
| --- | --- | --- |
| Organisms | Targeted Insect-pest | Reference |
| *Artemisia vulgari* | Potato Tuber Moth | [1] |
| *Beauveria bassiana* | Whitefly, Potato Beetle, Thrips | [10] |
| *Isaria fumosorosea* | Termites, Grasshoppers, Caterpillars and beetles | [73] |
| *Metarhizium anisopliae* | Spider mites, Black Vine Weevil | [40] |
| *Bacillus thuringiensis* | Larvae and Caterpillar | [12] |
| *Verticillium lecanii* | Nematodes, mites and thrips, mealy bug | [8] |
| *Metarhizium brunneum* | Sweet potato weevil | [22] |
| *Neozygites floridana* | Cassava green mite | [40] |

**2.4.2 Biochemical Pesticides**

Biochemical pesticides are natural substances that effectively deter pests from using any form of toxic mode to control them; they may control through physical interference with growth and development or attract or repel pests while enhancing plant resistance. Biochemical pesticides include substances such as plant growth regulators (PGRs), azadirachtin- a neem-based extract, kaolin clay which creates a physical barrier on plant surfaces and sex pheromones that disrupt mating as well as a variety of fragrant plant extracts that lures insect pests to traps. For instance, the extracts of castor seeds (*Ricinus communis*) effectively inhibited growth of post-harvest pathogens *Penicillium oxalicum* and *A*sp*ergillus niger* of yams (*Dioscorea alata*) in a dose dependent poisoned food technique experiment [19].

**Semiochemicals:** Semiochemicals are substances or mixtures of substances released from one organism that evokes either a behavioral or physiological response between members of the same or different species [48]. These semiochemicals influence insect pest behavior by insect-insect or plant-insect interaction. Host-plant volatiles provide one or more of four essential resources for the insect: feeding sites, mating sites, egg-laying sites and refugia [58,55]. Semiochemicals are effective at very low rates, often similar to levels that are found in nature. They are inherently volatile and can rapidly break down or deteriorate in the environment, highlighting the urgent need for careful management and consideration of their impact.

**Allelochemicals**: Allelochemicals are compounds produced by a single species that significantly influence the behavior of individuals from another species, forming an essential part of the intricate web of nature. This fascinating interaction creates interspecific effects that are formed to potentially shape ecologies. Among these powerful allelochemicals, we have allomones that provide an advantage to the emitting species, kairomones that benefit the receiving species, and synomones, with mutual benefit to both. However, knowledge of these kinds of interactions indicates the complexity within ecological relationships. It also has a significant and important message-that is, preservability-biodiversity.

**Pheromones**: It has been realized that the behavior of an individual species member is also affected by pheromones that the species member produces and communicates to the others. Thus, such fascinating chemical communication aids social interaction as well as fosters cooperation and cohesiveness in its members. It emphasizes the very strong interrelations which glue the individuals together.

**Insect pheromones**: Insect pheromones are the chemicals substances that insects produce and that are imitated in order to control insects in integrated pest management programs. As pheromone dispensers, the insects used in this process are confused by pheromone flumes that are dispersed throughout the environment. Insect pheromones are not true ‘insecticides’ since they do not kill insects but influence their olfactory system to affect behaviour [4]. To conclude, pheromones are absorbed by the perceiving insect's antennae and subsequently diffuse through microscopic cuticle pores into the sensilla's interior. The pheromone-binding proteins (PBPs) play a crucial role in transporting chemical substances to the chemosensory membranes, navigating effectively through the hydrophilic sensillum. Subsequently, the pheromone or pheromone-PBP complex interacts with a specific receptor protein, which transduces the chemical signal into an amplified electric signal by a second messenger system connected with neuronal machinery [22].

**Straight-chain lepidopteran pheromones**: Also known as SCLPs, are a type of pheromone that includes unbranched aliphatics, having a carbon chain length between 9 and 18. They can carry up to three double bonds and have an alcohol, acetate, or aldehyde functional group at the end.

**2.4.3 Plant Incorporated Protectants**

Plant-incorporated protectants, often referred to as PIPs, are genetically modified substances that cause plants to produce their own pest-fighting proteins. This is achieved by introducing specific genes into the plant's genome to enable the production of pesticidal proteins that would repel, kill, or otherwise deter insects and pathogens from the plant. The first *B*. *thuringiensis* (Bt) plant-incorporated protectant for use has registered 11 Bt plants, although five of these registrations are no longer active [41]. Bt toxin protein interacts with definite receptors on the plasma membrane of epithelial cells lining the insect mid gut, incorporates into the plasma membrane, and finally generates trans-membrane channels through which cell content is leaked leading to ultimately insect pest death [3]. For instance, potato expresses Cry3A or Cry3C which is effective against Potato beetle (*Leptinotarsa decemlineata*). However, Cry4Aa and Cry4Bb are particularly effective against disease vector mosquitoes and some fly species, offering potential biological managemt strategies for pest control.

**2.4.4 Other biopesticides**

***Azadirachta indica* (Neem)**: Neem is a powerful natural solution used to create a biopesticide that promotes environmental health offering a safe alternative that protects both plants and soil without causing any harm [64]. It is found that neem seed oil is active against softbodied insects, mites, and management of plant pathogens due to the presence of disulfides contributing to its bioactivity [51,50]. The essential ingredient present in neem is Azadirachtin. Seed extracts include substantial amounts of other triterpenoids such as salannin, nimbin, and their modified forms whose role is debatable but most observations suggest that azadirachtin as the most important active secondary metabolite [16,45]. Neem product activity is measured against 450-500 insect pest species in many countries worldwide, and from that, 413 insect pest species are found to be susceptible at various concentrations [24]. Azadirachtin interferes with insect endocrine system by preventing the pupation process and by antagonizing ecdysteroid and juvenile hormone activities. Indeed, azadirachtin was first isolated based on its extraordinary antifeedant activity towards the desert locust, and this plant secondary metabolite becomes the most effective locust antifeedant discovered till now [30].

**2.5 BIOLOGICAL CONTROL OF KEY-PEST OF TUBER CROPS**

Biological control is a way to protect plants from diseases without using chemicals. The biocontrol capacity of a microbe can result from production of antibiotic compounds, or enzymes capable of fungal cell wall lysis, depletion of iron from the rhizosphere, induced systemic resistance, and competition for niches with pathogens within the rhizosphere [34]. The production of antibiotics stands out as a highly effective and recognized mechanism for biocontrol. A number of biocontrol strains can also produce antifungal enzymes, for example chitinases, *β*1,3-glucanases, proteases, or lipases, with the capacity to lyse fungal cells [10]. Synthesis of low-molecular mass siderophores that chelate iron in the soil near roots can inhibit the proliferation of fungal pathogens (Kohl *et al*., 2019). For example, *Pseudomonas trivalis* strain BIHB 745 can produce siderophores [34], and the siderophores pyochelin and pyoverdine have been identified in *P*. *fluorescens* [54]. In addition, BCAs also trigger the production of growth phytohormones such as cytokinins (CK), indole-3-acetic acid (IAA), and gibberellins (GA) as well as the defense hormones salicylic acid (SA), abscisic acid (ABA), and jasmonic acid (JA) to improve growth and adaptive responses during stress conditions [5,2].

BCAs have emerged as a viable tool not only for controlling pathogens and pests, but also in improving plant growth and soil health, which make them an important tool in maintaining the one-health principle [29]. However, several enhancements such as scaling up production, optimizing formulation techniques and delivery methods, increasing cost-effectiveness, and meeting regulatory requirements are necessary before they can be successfully implemented in the field [44]. The global scientific community is at pace with exploring BCAs in terms of understanding the mechanisms behind their strategies to control pathogens [37]. BCAs includes predators, parasitoids, nematodes, bacteria, viruses and fungi. Some BCAs and their examples are mentioned in table 2. Some insect pests of tuber crops and their natural enemies are mentioned in the table 3.

**Table 2: Different types of Biocontrol Agents (BCAs)**

|  |  |
| --- | --- |
| Biocontrol Agents | Examples |
| Predators | Ladybugs, dragonflies, lacewings, pirate bugs, rove and ground beetles, aphid midge, centipedes |
| Parasitoids | Ichneumonid wasps, braconid wasps, chalcid wasps, tachinid flies |
| Nematodes | *Heterorhabditidae* sp., *Mermithidae* sp., *Rhabditidae* sp., *Steinernematidae* sp. |
| Bacteria | *Bacillus* *thuringiensis*, *Bacillus* *popillae* |
| Fungi | Cytoplasmic polyhedrosis (CPV) and Entomopoxy viruses (EPN) |
| Viruses | *Beauveria* *bassiana*, *Trichoderma* *viride* |

**Table 3: Insect-pest of tuber crops and their major bio-control organism**

|  |  |  |
| --- | --- | --- |
| Crops | Pest | Major Bio-control organisms |
| Cassava | *Paracoccus marginatus* | *Cryptolaemus montrouzieri, Anagyrus loecki, Pseudleptomastix mexicana, Acerophagus papayae* |
|  | *Bemisia tabaci* | *Prospaltella flava, Coccinellam septempunctata* |
|  | *Aleurodicus dispersus* | *Nephaspis oculatus, N. bicolor, Encarsia haitiensis, Axinoscymnus puttarudriahi and Cheilomenes sexmaculata* |
|  | *Aonidomytilus albus* | *Chilocorus nigritus,Chilomenes*  *sexmaculata, Scolothrips indicus* |
|  | *Rhyzopertha dominica* | *Anisopteromalus calandrae, Lycto-coris campestris, Acarophenax assanovi* |
|  | *Sitophilus oryzae* | *Anis, Lariophagus distinguendus* |
| Sweet Potato | *Cylas formicarius* | *Rhaconotus sp. and Bracon sp.* |
|  | *Agrius convolvuli* | *Trichogramma australicum, T. achaea, T. agriae* |
|  | *Aspidomorpha miliaris* | *Cassidocida aspidiomorphae and*  *Tetrastichus colemani* |
| Yams | *Aspidiella hartii* | *Physcus comperi, Adelencyrtus moderatus* |
|  | *Ferrisia virgata* | *Allograpta javana, Triommata coccidivora* |
| Aroids | *Aphis gossypii* | *Aphelinus mali, Coccophagus cowperi, Aphidencyrtus aphidivorus, Menochilus sexmaculatus, Verania discolor, Pseudospidimerus cirumflexus* |
|  | *Spodoptera litura* | *Charops hersei* |
|  | *Monolepta signata* | *Eocanthecona furcellata* |
| Chinese potato | *Spoladea recurvalis* | *Microgaster psarae* and *Leptobatopsis indica* |

3. CONCLUSION

Biopesticides offer a highly effective alternative to synthetic pesticides in the management of crop pests, proving their worth in sustainable agriculture [57]. Natural products are a compelling choice for those who care about the environment, their biodegradable nature ensures they break down naturally, minimizing pollution and helping to protect our planet for future generations [53]. Biopesticides have exceptionally short pre-harvest intervals, guaranteeing their safety for use on fresh fruits and vegetables [25]. They are formulated to impact only specific organisms, ensuring that beneficial ones, such as natural adversaries, remain unaffected [71]. Their effectiveness in minimum quantities makes them a powerful ally in sustainable pest management, ultimately fostering the principles of sustainable agriculture.

Biopesticides offer a safe and effective solution for both applicators and consumers, as they are completely non-toxic [14]. Therefore, biopesticides can suitably be incorporated into integrated pest management (IPM) which helps reduce the amounts of chemical pesticides used to manage crop pests [72]. To enhance agricultural production while preserving both the environment and the health of farmers, the National Farmer Policy of 2007 firmly promoted the use of biopesticides. Furthermore, it emphasizes that biopesticides will be supported and promoted at the same level as chemical pesticides. The development of biological pest control techniques must be prioritized, and farmers in particular and the general public must be taught how to handle and apply these control approaches. All of this will contribute to a wider comprehension of the advantages of biopesticides as environmentally friendly substitutes. Nevertheless, IPM, INM, ICM, and GAP are necessary in the current environment, and their application will guarantee health and quality of life.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

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

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