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Biological Control of Pests in Major Tropical Vegetable Crops: A Review

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ABSTRACT

India stands as a global agricultural powerhouse, employing over 60% of its population in farming and related sectors. Agriculture forms a significant pillar of the nation's GDP, with vegetables being a cornerstone of its horticultural output. Despite advancements in vegetable production, the sector faces myriad challenges, including insect infestations, diseases and other biotic and abiotic factors that compromise yield and quality. This review article delves into the biological control of pests in key tropical vegetable crops like brinjal, tomato, chili, okra and cucurbits. It explores the use of biological control agents such as predators, parasitoids and pathogens as part of integrated pest management strategies aimed at reducing the dependency on synthetic pesticides. It provides an in-depth analysis of common pests such as whiteflies, aphids, mealybugs and thrips, as well as crop-specific pests like brinjal and bhendi shoot and fruit borers. The paper underscores the advantages of biological control, including its environmental sustainability and reduced risk of pest resistance, while also acknowledging its limitations such as slower pest elimination rates and higher costs. It calls for concerted efforts from governmental bodies, NGOs and agricultural institutes to promote awareness and training in biological control methods. The focus of the review is to advocate for a paradigm shift towards sustainable and effective pest management practices in India's vegetable farming sector.

Key words: *Bacillus thuringiensis, Beauveria bassiana,* Parasitoids, Pests, Predators.

India is one of the world's largest agricultural countries, with more than 60% of the population employed in agriculture and related activities. Agriculture in India contributes an 18.6% share of the national GDP. India produces almost all crops, including cereals, vegetables and cash crops (Vanitha *et al*., 2013; APEDA, 2020). Numerous horticultural products are exported to other countries, generating significant amounts of foreign exchange. These products include fruits, vegetables and flowers. Vegetables play a significant role in horticulture and are grown throughout the country, with key crops such as brinjal, tomato, chili, okra and cucurbits (National Horticulture Board, 2018). Vegetables are critical sources of protein, vitamins, minerals, dietary fiber, micronutrients and antioxidants in our daily diets. They provide nutrition and also contain a variety of phytochemicals, such as flavonoids, glucosinolates and isothiocyanates, that aid in the prevention and treatment of various diseases. While vegetable output and productivity have increased, cultivation of these crops is constrained by a variety of factors, including insect pests, diseases and other biotic and abiotic factors. Among them, insect pests attack vegetables at various stages of growth, resulting in significant reductions in production and quality (Sharma *et al*., 2017). They can cause variable damage to plants in protected structures such as net houses, polyhouses and glasshouses, as well as in open fields (Rai *et al*., 2014). The majority of insects and mites attack tropical crops such as brinjal, tomatoes, chilies, okra and cucurbits. Aphids, red spider mites, jassids and whiteflies are major pests that can cause damage at various stages of growth. aphids, jassids, whiteflies, fruit and shoot borers, Hadda beetles and mealy bugs are all examples of these pests. While a variety of pest management techniques are available, chemical pesticides are the most frequently used, particularly during the post-green revolution years. Nonetheless, the widespread and unregulated use of chemical pesticides has resulted in a slew of issues, including chemical residues in finished goods, adverse effects on human and animal health and negative environmental consequences. On the other hand, several research findings indicate that the majority of insect pests have evolved resistance to commonly used pesticides. Pests are also making a comeback in several regions of the country. Researchers and farmers have been examining alternative or corrective pest management techniques in order to achieve sustainable crop protection, production and environmental safety.

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Finally, biological control has gained widespread acceptance as an environmentally responsible alternative to synthetic pesticides for managing insect pests in crops. Living organisms and their products are used to keep pests below the economic threshold level (ETL), while also protecting natural enemies (Altieri *et al*., 2005; Mahr *et al*., 2008).

Significant advances in biological control of insect pests have occurred in recent decades and over the last 50 years, biological control has remained a critical component of integrated pest management, demonstrating slow but hopeful progress in Integrated Pest Management (IPM) (Orr, 2009). The following paragraphs discuss the pests that attack the major tropical vegetable crops and their biological control measures.

Pests of major tropical vegetable crops in india and the extent of their damage

Vegetable crops are subjected to a wide range of insect pests and these are the primary impediments to vegetable production, both on and off the field. Insects cause a variety of injuries depending on their feeding patterns (Table 1). Apart from direct injury, they serve as a vector for a variety of viral infections in persistent (Tomato Yellow Leaf Curl Virus transmitted by the whitefly), semi-persistent (Cucumber Mosaic Virus by aphids) and non-persistent modes (Potato Virus Y by aphids) (Rai *et al*., 2014). Numerous studies conducted at various stages of crop development predicted crop losses of 30%-40%. (Rai *et al*., 2014). The primary factors that contribute to pest outbreaks and epidemics are changes in production strategies such as intensive monoculture, the introduction of high-yielding but vulnerable varieties and hybrids and the increased inputs required under varying climatic conditions. Due to seasonal changes and favourable environmental conditions, minor pests have become a significant problem in some instances (Vanitha *et al*., 2013; Rai *et al*., 2014). This has a direct economic impact, as India exports fresh fruits and vegetables to a large number of trading nations. Vegetable exports account for approximately 16.27 per cent of foreign earnings (Shivalingaswamy *et al*., 2006). Shoot and fruit borers are the primary pests to vegetable crops. They cause undesirable symptoms such as wilted terminal shoots, boreholes in the stem and excreta-filled fruits.

The brinjal fruit and shoot borer, scientifically known as *Leucinodes arbonalis*, is recognised as a significant pest in agriculture. This species is classified under the family Crambidae and is notable for its highly destructive behaviour in brinjal cultivation regions. Consequently, it is recognized as a significant pest of brinjal crops. The larvae exhibit a behaviour of penetrating the stem shortly after the seedlings are transplanted. As they progress in their development, they proceed to penetrate the fruits and consume them, resulting in detrimental effects on the plant. This not only diminishes the market worth of the fruits but can also render them unsuitable for harvesting, particularly in severe instances (Raina and Yadav, 2018; Nishad *et al*., 2019). The number 17 is a positive integer that falls between 16 and 18 on the number line. The infestation of pests has posed a significant challenge to the cultivation of brinjal across India, leading to substantial crop losses. Various studies have reported crop losses ranging from 20% to 80% (Raju *et al*., 2007), 85% to 90% (Misra, 2008) and 70% to 92% (Chakraborti and Sarkar, 2011) during different seasons of the year. Farmers rely heavily on consistent and planned applications of chemical-based insecticides to effectively control pests.

Additionally, they result in the shedding of floral buds and the drying of leaves. Sap sucking insects such as leaf hoppers and aphids suck the plant sap, causing the foliage to wilt, crinkle, curl downward and die. Nymphs and adults are the most destructive stages (Shivalingaswamy *et al*., 2002). Additionally, ants can cause damage to plants. They are indirect pests that cause damage to plants by cutting leaves to cultivate fungus gardens and also transport honeydew-producing homopteran insects between plants. This is a mutualistic relationship in which the homopterans benefit from increased opportunities to feed on a variety of plants and the ants benefit from the honeydew. Eco-friendly pest management strategies have gained prominence and significance in India following the World Trade Organization's (WTO) signing of the general agreement on trade and tariffs (GATT). Biological control measures are being integrated with other control methods to maximize effectiveness over a range of time periods and environmental conditions.

India's need for biological pest management

Vegetable production is expected to reach 188.91 million tonnes in final estimates, up from 183.17 million tonnes in 2018-19 (Agriculture Post, 2021). This is critical in order to meet the country's growing food demand. Apart from superior farming and crop output, farmers frequently confront a number of challenges, including an excessive reliance on inputs, particularly chemical fertilizers and nutrients, in order to obtain desired outcomes and management of numerous insect pests and illnesses. This has resulted in high cultivation and investment costs, which are reflected in the returns. On the other hand, chemical pesticides and fertilizers have contaminated the environment and harmed human and animal life. This has resulted in significant improvements in farmers' attitudes toward and use of pesticides. Biological control is one such strategy, in which a variety of biocontrol agents are utilized to successfully manage pests in IPM. There is no deliberate introduction or manipulation of beneficial bacteria or insects for the goal of biological control. The most promising control chemicals are repeatedly evaluated against a target pest, followed by mass manufacture and commercial release under a controlled scenario (Hodek *et al*., 2012).

Management of insect and mite pests using biological control agents

In India, the majority of plant protection measures are entirely reliant on chemical pesticides. Farmers apply pesticides on

Table 1: Pests of major tropical vegetable crops and their symptoms (Dhaliwal and Arora, 2016; Reddy, 2018).

Pest	Crop	Damaging stage	Symptoms
Aphid (*Myzus persicae*)	Tomato, chilli	Nymphs and adults	Curling of leaves and growth is affected.
Aphid (*Aphis gossypii*)	Bhendi, Tomato	Nymphs and adults	Curling of leaves and stunted growth.
Whitefly (*Bemisia tabaci*)	Bhendi, tomato, chilli	Nymphs and adults	Infested leaves curl and dry. These insects transmit yellow vein mosaic virus in bhendi and leaf curl virus in tomato.
Mite (*Tetranychus spp.*)	Brinjal, bhendi, tomato	Nymphs and adults	Yellowing and discolouration of leaves. Presence of silken webs on infested plant parts.
Mealy bug (*Phenacoccus solenopsis*)	Bhendi, tomato	Nymphs and adults	Tomato: Deformation and distortion of terminal growth, foliar yellowing, leaf wrinkling and puckering were observed. Bhendi: Nymphs and adults suck cell sap from all aerial plant parts and makes the plant weak.
Thrips (*Thrips tabaci*) (*Frankliniella schultzei*)	Tomato	Nymphs and adults	White to Silvery patches on emerging leaves. Vector of tomato spotted wilt virus (TOSPO virus)
Leaf miner (*Liriomyza trifolii*)	Tomato, Cucurbits	Maggot	Serpentine mines into the leaf between the upper and lower surfaces and feed on the mesophyll tissues.
Fruit borer (*Helicoverpa armigera*)	Tomato, Bhendi, chilli	Caterpillar	Caterpillars bore the fruit and feed on the pulp.
Oriental leafworm moth (*Spodoptera litura*)	Tomato, chilli	Caterpillar	Caterpillars skeletonize the leaves. They scrape the green matter in the leaf leaving the epidermis alone.
Brinjal shoot and fruit borer (*Leucinodes orbonalis*)	Brinjal	Caterpillar	Boreholes in tender shoots resulting in drooping or drying of tips. In fruits, boreholes are plugged with excreta.
Hadda beetle (*Henosepilachna vigintioctopunctata*)	Brinjal	Grubs and adults	Skeletonization of leaves.
Tomato pinworm (*Tuta absoluta*)	Tomato	Larvae	Mining of leaves, stem and pinholes on fruits.
Chilli thrips (*Scirtothrips dorsalis*)	Chilli	Nymphs and adults	Inward curling of leaves, stunted plant growth, dropping of flowers buds and fruits.
Chilli mite (*Polyphagotarsonemus latus*)	Chilli	Nymphs and adults	Infestation is found on lower side of leaves. Leaf curls downward and turn dark green, lower surface is brown with shiny coating.
Shoot and fruit borer (*Earias vittella)* (*Earias insulana)*	Bhendi	Caterpillar	Caterpillars bore into the terminal tender shoots that lead to withering and drooping down of growing tips. Boreholes in the fruits and infested fruits are unfit for marketing.
Jassids(*Amrasca devastans*)	Bhendi	Nymphs and adults	Tender leaves turn yellow, the leaf margins curl downward and reddening begins. In severe situations, a condition known as leaf hopper burn is developed. The leaves withered and were shed and the crop's growth was slowed.

Table 1: Continue...

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Pumpkin beetle (*Aulacophora foveicollis*)	Cucurbits	Grubs and adults	Grubs consume both roots and stems. Adults pierce leaves irregularly.
Pumpkin caterpillar (*Diaphania indica*)	Cucurbits	Caterpillar	The early instar larvae scrape the chlorophyll material from the leaves, whereas the later instar larvae fold and web the leaves and feed within. Additionally, it feeds on flowers and bores into fruit that is growing.
Melon fly (*Bactocera cucurbitae*)	Cucurbits	Maggots	Maggots feed on the pulp and seeds inside. The infested fruits may fall prematurely.

a calendar-based schedule. Given the high value of vegetable crops, even a little infestation can result in a loss of quality and reduced yields. As a result, farmers are regularly spraying pesticides, even if the chemical is below the ETL. This has become into a routine activity for vegetable growers throughout the years. Without being observed, natural flora and animals are being harmed, as well as economically valuable insects such as predators, parasitoids and bees. Farmers must therefore utilize organic management measures to save these beneficial insects while also protecting the environment (Altieri *et al*., 2005; Mahr *et al*., 2008; Halder *et al*., 2011). In recent decades, continuous progress has been made in India's biological management of insect pests. However, it must be supplemented with an increasing number of natural enemies and microbial biocontrol agents in order to manage insect pests successfully, starting with laboratory research, mass production and release in vegetable crops for a specific pest.

Predators

Predators are beneficial insects and other vertebrate animals that hunt and consume pests directly. Ladybugs (ladybird beetles) (Fig 1 A, B), preying mantids, green lacewings (Fig 1 C, D), carabid beetles, rover beetles, hoverflies, minute pirate bugs, mirid bugs, big-eyed bugs, arachnids such as spiders and predatory mites are all examples of general predatory insects. Most ladybird species are considered beneficial because they are predators of Homoptera or Acarina, many of which are pests. These predatory ladybirds help to regulate the populations of their prey and, in some cases, provide a high amount of control. People may benefit when ladybirds naturally offer a high degree of pest management, or when combined with other predators, parasitoids and diseases to provide a significant amount of pest population management. That is, gardeners, growers and farmers may benefit for free as they have no or little pest concerns. The adults and larvae of ladybug beetles consume a variety of tiny, soft-bodied insects, as well as their eggs and larvae. The majority of these predators are generalists who prey on a variety of pests, including phytophagous insects and mites. Predators typically have either chewing or sucking mouth parts and some predators have both (Sampaio *et al*., 2009). Only select insect orders have predatory insects. For example, dragonflies belong to the order Odonata; aquatic nymphs are predatory and breathe through their gills, whereas adults are powerful flyers. They can capture prey while flying over gardens and agricultural fields. Another order is Mantodea, which contains carnivorous mantids. They are exceptional hunters, concealing themselves on leaves and plant surfaces to deceive their prey. They have strong front legs that are well-adapted for catching prey. Similarly, Neuroptera contains green lacewings and antlions, whose larvae feed on insects and adults on pollen and nectar (Sampaio *et al*., 2009). Order rover flies are a suborder of Diptera that employ the same tactics as dragonflies to grasp their victim. Coleoptera includes ladybugs, which are exceptional predators belonging to the Coccinellidae family. Numerous mites belonging to the family Phytoseidae have also been observed to exhibit predatory behaviour towards other phytophagous mites.

Several natural predators can be introduced to control mealybug infestations, including the green lacewing, parasitoid wasps and the beetle known as the "mealybug destroyer". These natural predators are more commonly used for outdoor infestations or in greenhouses (The Spruce, 2023).

Several studies have highlighted the effectiveness of various biological agents in controlling aphid infestations. One study conducted by Hodek *et al.* (2012) emphasized the role of ladybugs (Coccinellidae) as efficient predators of aphids. Ladybugs are known for their voracious appetite for aphids and their introduction into aphid-infested crops has been shown to significantly reduce aphid populations (Hodek *et al*., 2012). Thrips are a major pest for many crops worldwide and their control is often hindered by their thigmotactic habits, which make it difficult to apply chemical control methods. Biological control agents, such as predatory insects and mites, have been suggested as an eco-friendly approach to manage thrips pests. One such predator is the banded thrips *Aeolothrips intermedius*, whose larvae are considered the primary native predator of the onion thrips *Thrips tabaci* (Abenaim *et al*., 2022). Another potential predator is the minute pirate bug *Orius insidiosus*, which has been shown to be an effective control agent for thrips (Silva *et al*., 2023). In addition, the predatory mite *Amblyseius swirskii* and the pirate bug *Orius laevigatus* have been used against the western flower thrips *Frankliniella occidentalis* in greenhouse conditions (Botond *et al*., 2020).

Parasitoids

Parasitoids are living organisms that live on or inside their hosts and feed on them. These parasites can thrive both within and outside the body of an insect. The parasites feed only on the immature stage of the insect host. Adult females of several parasites (for example, many hymenopteran wasps that prey on scale insects and whiteflies) feed on and provide a simple biological control supply for their hosts (Sanda and Sunusi, 2014). They are classified according to their prey stage, which is attacked by a parasite, into egg parasitoids, which develop fully inside the egg of another insect. Egg-larval parasitoids are those that oviposit inside their host's egg but complete their metamorphosis in the host larvae. Additionally, parasitoids are classified as larval, pupal and larvae-pupae. In some instances, the parasitoid uses the insect's adult stage as a host (ectoparasitoid) (Sampaio *et al*., 2009). When a parasitoid develops on the host, it is called an ectoparasitoid (Fig 2 A); when it develops within the host, it is called an endoparasitoid (Fig 2 B).

Diptera (flies) and Hymenoptera (wasps) account for the vast majority of parasitic insects. More than a dozen Hymenoptera families contain wasps that are parasitic on other wasps. Aphidiinae (a subfamily of Braconidae) are aphid predators that feed on aphids, which are a pest in many crops. Trichogrammatidae is another family that parasitizes eggs. Aphilinidae, Encyrtidae, Eulophidae and Ichneumonidae are some of the other parasitoid families (Flint and Dreistadt, 1998). In India, 37 parasitoid species have been discovered on *Helicoverpa armigera*, although only eight are deemed significant.

Trichogramma spp. (Fig 2 C) was observed with an egg parasitism rate of 80% on tomato plants infested with *Neoleucinodes elegantalis* (Fragoso *et al*., 2019). The adult female wasp lays eggs in each aphid host; the eggs hatch into larvae that feed on and kill aphids. Aphids that have been parasitized will die and become mummies. Among the caterpillar parasites is the *Hyposoter exiguae* wasp (Fig 2 D),

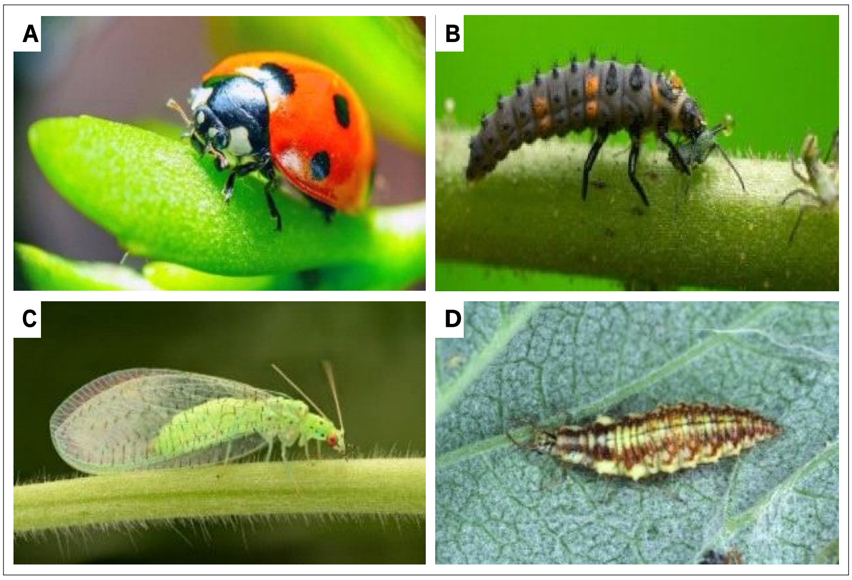

Fig 1: A) Ladybug adult (Trunfio, 2019), B) Ladybug larva (Larsson, 2017), C) Green lacewing adult (Vila, 2021), D) Green lacewing larva (Kellen, 2018).

which lays eggs on armyworms and consumes the insect host. Tachinid flies are parasitic flies that feed on a number of different insects. They lay their eggs on caterpillars, which hatch and burrow into the flesh of the host, feeding on its internal contents (Hein *et al*., 2004).

Trichogramma chilonis Ishii stands out as the most efficacious biocontrol agent among the available options. This particular agent is classified as an egg parasitoid, specifically targeting the egg stage of the pest in question (Krishnamoorthy, 2012).

According to Alam *et al.* (2006), the regular introduction of the egg parasitoid *Trichogramma chilonis* Ishii at a rate of 1 g of parasitized eggs per hectare per week, along with the larval parasitoid *Bracon hebetor*. The population density of 800-1000 adults per hectare per week, has proven to be an effective method for lowering the population of the Brinjal Shoot and Fruit Borer. According to Cork *et al.* (2003), the installation of Brinjal Shoot and Fruit Borer sex pheromone lures in traps has been found to effectively mitigate fruit damage and enhance yield, with a recommended density of 100 traps per hectare. According to Alam *et al.* (2003), for optimal attraction, it is recommended to position traps either at the level of the canopy or slightly above it.

One approach involves the use of parasitic wasps, such as *Aphidius spp*. on aphids. These tiny wasps lay their eggs inside aphids and as the wasp larvae develop, they consume the aphids from the inside, ultimately leading to aphid mortality (Van Lenteren, 2012).

Insect pathogens

Similar to plant microorganisms, microscopic organisms such as protozoa, viruses, actinomycetes and nematodes attack and destroy insect and mite pests.

Bacteria

Bacterial pathogens are spore-forming, rod-shaped bacteria from the *Bacillus* genus. Insectpathogenic bacteria with the potential to be employed in biological pesticides are limited to three types of spore-forming bacteria: *Bacillus thuringiensis, Bacillus sphaericus* and *Bacillus papillae.*

S. Ishitawa, a Japanese scientist, discovered *Bacillus thuringiensis* in 1901. *Bacillus thuringiensis* is a facultative anaerobic gram-positive bacterium that produces protein inclusions near the endospore. These proteins are naturally crystalline and dissolve only at an alkaline pH. By transcription and translation of the *cry 1 ac* gene, *B. thuringiensis* produces the cry 1 ac protein. These proteins breakdown in the alkaline pH of lepidopteran caterpillars' guts, causing harm to the gut epithelial cells. As a result of the injury, the caterpillar is unable to feed and eventually dies and turns to dark brown colour (Fig 3 A).

Another bacterium, *Pseudomonas fluorescens*, has shown potential in combating root and stem-feeding insects that often plague vegetable crops (Péchy-Tarr *et al*., 2008). The utilization of these bacteria provides an environmentally friendly alternative to chemical pesticides, promoting sustainable agricultural practices and ensuring the safety of the produce (Glare *et al*., 2012).

The symbiotic relationship between *Xenorhabdus* bacteria and entomopathogenic nematodes has been harnessed to combat soil-borne pests that threaten the roots of vegetable plants, providing a two-pronged approach to pest management (Elbrense *et al*., 2021). As the global demand for organic vegetables rises, the role of these bacteria in safeguarding crops without compromising environmental health becomes even more paramount.

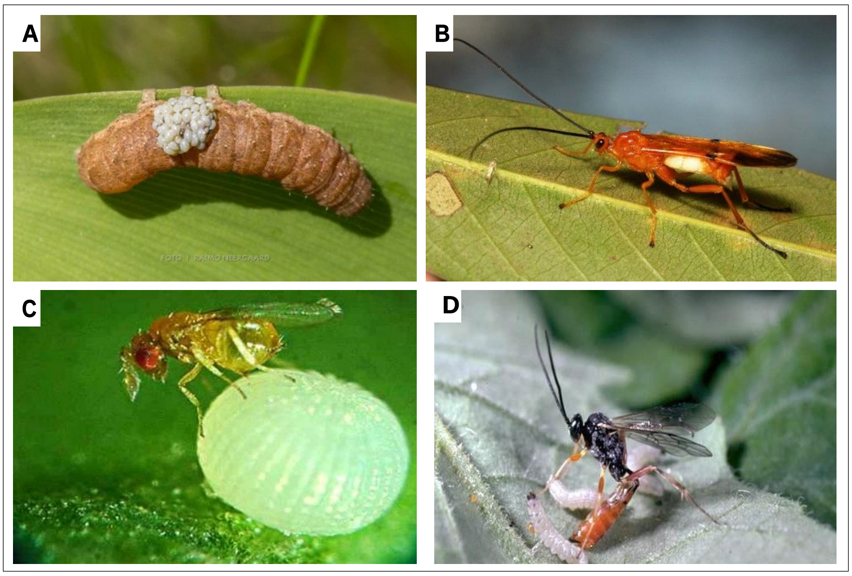

Fig 2: A) Larvae of ectoparasitoid wasp (Raimo, n.d.), B) Endoparasitoid Braconid wasp (Horstman, n.d.), (C) *Trichogramma chilonis* parasitizing egg (Marshall Grain Co., 2022), D) *Hyposoter exiguae* wasp (Clark, n.d.).

Virus

Around 1600 strange viruses have been found to infect roughly 1100 insect and mite species. A category of baculoviruses infects around 100 species of insects. This baculovirus classification accounts for more than 10% of all entomopathogenic viruses. Baculoviridae is one of those viral families that infect solely invertebrates, which makes them ideal insect pathogens due to the low risk of cross-infection with mammals. Baculoviruses are circular double-stranded DNA genomes contained in rod-shaped particles. Baculoviruses are widely considered to be safe, posing little threat to non-target animals. Baculoviruses do not produce metabolites or poisons and, unlike bacteria and fungi, are incapable of replication outside of their host. This differentiation between bacteria and fungi is critical.

The larvae consume occlusion bodies (polyhedra for nuclear polyhedrosis viruses and granules for granular viruses). In a highly alkaline midgut pH, the occlusion body protein dissolves and is destroyed by host alkaline proteases. Polyhedral virus particles released into the environment bind to the midgut's peritrophic membrane. The lipoprotein of the virus forms a covalent link with the plasma membrane of gut wall cells, releasing nucleocapsids into the cytoplasm. The nucleotide transports virus DNA into the cell's nucleus, where virus gene activation is initiated. The virus rapidly replicates and eventually infects the host. Infected insects quit feeding and the larvae develop a pinkish-white colour on the ventral side due to polyhedral structure aggregation. If the infection is not treated at the larvae's advanced stage, the larva becomes flaccid, the skin becomes flimsy and the larva eventually ruptures. Sick larvae crawl to the apex of the plant and dangle upside down from there in the field. Treetop disease is the term used to describe the ailment (Fig 3B). *Spodoptera litura* and *Helicoverpa armigera* are both very susceptible to NPV.

NPVs have long been recognized as an integral aspect of integrated pest management techniques against a number of insect pests (Tanga *et al*., 2011), particularly lepidopteran pests such as moths and butterflies (Rao *et al*., 2015). Another study was conducted to determine the toxicity of NPV against the 2nd and 4th instar larvae of *S. litura* from diverse areas. Three concentrations of NPV were prepared: NPV-34 $\times$ 10^9, NPV-23 $\times$ 10^9 and NPV-12 $\times$ 10^9 POB ml/litre. The study discovered that high concentrations resulted in the highest larval mortality rate of 83.28 per cent.

NPVs were discovered to have a direct influence on eggs, larvae, pupae and adults in this study. The application of NPV shortened the duration of each developmental stage (Yasin *et al*., 2020). Another study examined the combined effect of NPV, chlorantraniliprole and *Azadirachta indica* on *Helicoverpa armigera* and *S. litura* larvae at various instar stages. The study discovered that whereas combined treatments had a high death rate, individual applications had a low mortality rate (Qayyum *et al*., 2015).

Fungus

Louis Pasteur pioneered the use of fungus in vineyards to control microscopic insect pests. In contrast to entomopathogenic bacteria and viruses, which enter the host insect *via* the mouth, entomopathogenic fungi (Fig 3 C) can enter *via* the outer integument (Patil *et al*., 2021). After adhering to the host, the fungus penetrates the insect's body wall *via* spore-derived hyphae. Invasion of the cuticle by hyphae occurs *via* wounds, segmental junctions, or sensory organs. The insect dies as a result of significant fungal

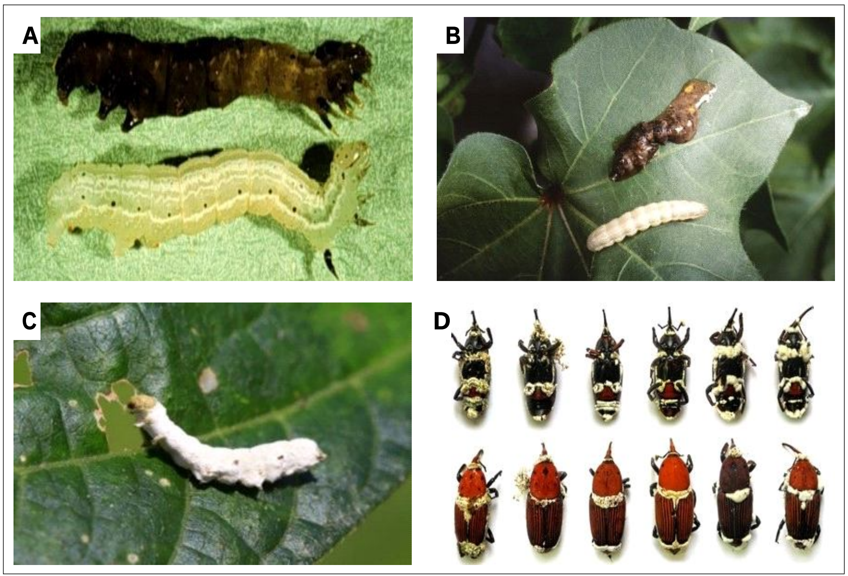

Fig 3: A) Moth larva affected by *Bacillus thuringiensis* (PortalFruiticola.com, 2018), B) Caterpillar affected by NPV (Tree top disease) (BreedingButterflies.com, n.d.), C) Moth larva af-fected by entomopathogenic fungus (*Beauveria bassiana*) (Zhang, n.d.), D) Weevils infected by *Metarhizium anisopliae* (Protasov, n.d.).

growth in the haemolymph and toxin poisoning caused by the fungal toxin.

Paecilomyces is a widespread fungus best known for its nematophagous ability, but it has also been found as an insect parasite and biological control agent of numerous fungi and phytopathogenic bacteria *via* unique mechanisms of action. Numerous species of the genus *Paecilomyces* produce a diverse array of secondary metabolites with a variety of chemical structures and biological activities, including insecticidal (Asaff *et al*., 2005), nematicidal (Saha *et al*., 2016). *Paecilomyces* have been found to parasitize fungi and nematodes (Munawar *et al*., 2015). When the pathogen and the antagonist come into contact, enzyme complexes are formed and/or released, resulting in antagonist development at the expense of the host (Talibi *et al*., 2014). Lipases, proteases and chitinases are the most effective entomopathogenic enzymes (Khan *et al*., 2004). Thus, it has been demonstrated that the synthesis of these enzymes by *P. fumosoroseus* is effective against *Tenebrio molitor* (Gómez *et al*., 2017), *Trialeurodes vaporariorum* (Castellanos-Moguel *et al*., 2007) and other infections. Numerous studies on *Paecilomyces'* nematicidal effect have been conducted. Through spore germination and subsequent hyphal branching and appressoria development, species of this genus, notably *P. lilacinus*, are capable of penetrating both the eggshells and structural components of several nematode species' juvenile and adult stages (Dong *et al*., 2007). It has been discovered that the creation of enzymes like as amylases, lipases, proteases and chitinases associated with this species has a nematicidal effect (Khan *et al*., 2004). Overexpression of these enzymes boosts *P. lilacinus*'s virulence and parasitic capacity against *Meloidogyne incognita, Panagrellus redivivus* and *Caenorhabditis elegans* (Yang *et al*., 2011).

Metarhizium anisopliae has the potential to be an extremely beneficial pathogen for insect pests and is currently being studied for myco-biocontrol of a number of well-known insect pests (Fig 3 D). Hasan *et al.* (2002) explored how *M. anisopliae* generates spores via solid-state fermentation. In a variety of horticultural growing media (Peat, coir, bark and peat blends with 10% and 20% composted green waste), the entomogenous fungus *Metarhizium anisopliae* V275 was more effective at killing western flower thrips pupae than chemical insecticides (imidacloprid, fipronil) (70-90% versus 20-50%). By including *M. anisopliae* in the growing media, drench treatments in coir and peat mixtures containing 20% composted green waste, insect pests were controlled more effectively. *M. anisopliae* in combination with sublethal doses of insecticides gives slightly better control than the individual control agents, but no evident additive or synergistic effects are observed. *M. anisopliae* is effective in all growth circumstances and is compatible with conventional insecticides, which makes it an appealing candidate for thrips control in an integrated pest management program (Ansari *et al*., 2007).

Studies have evaluated the efficacy of novel insecticide molecules and entomopathogens to control Hadda beetle in brinjal. Among the biopesticides, *Metarhizium anisopliae* and neem oil have been found to be effective against Hadda beetle. In laboratory and field experiments conducted at the Indian Institute of Vegetable Research, Varanasi, *Metarhizium anisopliae* and neem oil provided the highest protection over control and indicated compatibility and synergistic activity at a 1:1 combination (Kodandaram *et al*., 2014). Another study found that *M. anisopliae* IIVR strain was most promising against Hadda beetle, followed by *M. anisopliae* commercial formulation, whereas neem oil was the most effective biopesticide against the pest (Halder *et al*., 2017). These studies suggest that entomopathogens and neem oil have the potential as eco-friendly and sustainable approaches to managing Hadda beetle in brinjal.

The microbial control agents *Bacillus thuringiensis, Beauveria bassiana* and *Metarhizium anisopliae* have been tested by Sabbour, (2015) against the tomato pinworm *Tuta absoluta* under laboratory and greenhouse conditions. The results showed that these agents were effective in reducing infestation and mortality rates of *T. absoluta*, with *M. anisopliae* showing the highest percentage of parasitism after treatments. A combination of mass release of *Trichogramma pertiosum* and *B. thuringiensis* resulted in only 2% fruit damage in South America.

Aphids, thrips, grasshoppers and certain beetles are all susceptible to white muscadine disease, which is caused by the entomopathogenic bacteria *Beauveria bassiana*. Unlike *Nosema locustae*, it does not require the host to consume the spores; instead, *B. bassiana* spores simply contact a host (ARBICO Organics, n.d.). Physical forces attach conidia to the host cuticle, followed by germination and penetration of cuticular layers, which are accelerated by hydrolytic enzymes (*e.g*., proteases, lipases, chitinases), mechanical pressure and other variables (Ortiz-Urquiza and Keyhani, 2013). When the expanding hyphae reach the nutrient-rich haemolymph, the fungus can form single-celled, yeast-like blastospores (or hyphal bodies), which are specialized structures that enable the fungus to rapidly reproduce and exploit resources, invade interior tissues and evade detection by the host immune system (Humber, 2008). Various pathogenic metabolites (antimicrobial peptides) are produced during colonization. They contribute to host immunological suppression, culminating in the destruction of host internal tissues and nutrient depletion, which eventually culminate in host death (Gibson *et al*., 2014). *B. bassiana* surrounds the body with a white mold that develops an increasing number of infectious spores (ARBICO Organics, n.d.).

The bhendi fruit and shoot borer, *Earias vitella* is a major pest of many crops, including okra and cotton, in India. While there is limited research on biological control methods specifically for *Earias vitella*, some studies have evaluated the efficacy of biological control agents on other pests that may be effective against *Earias vitella*. Spinosad and *Bacillus* *thuringiensis* have been found to be effective against shoot and fruit borer pests in okra (Choudhury *et al*., 2021).

A self-sustaining granular fungal treatment has been developed to control *Frankliniella occidentalis*, also known as the western flower thrips. The treatment combines cooked, oven-dried millet with *Beauveria bassiana* strain GHA to potting soil, which increases spore production and persistence of the fungus in the soil (Davari *et al*., 2021). The method is relatively inexpensive and easy for growers to use in greenhouses because granular formulations of *B. bassiana* are not commercially available.

Nematodes

Neoplectana carpocapsae is the most often employed entomopathogenic nematode for insect management and one of its strains, DD-136, is widely used to control insect pests infesting agricultural crops, vegetables and orchards (Patil *et al*., 2021). Fig 4 A depicts the life cycle of an entomopathogenic nematode.

The nematode *Steinernema feltiae* is used to manage *Helicoverpa armigera* and a few soil pests and termites, while *Steinernema soodi* is used to control *Galleria melonella* (Fig 4 B). *Rhabditis* sp. (Fig 4 C) is used to combat white grubs (*Holotrichia serrata*) and *Tetradonema plicansis* is used to fight sciarid flies and cultivable mushroom pests.

Protozoans

Microsporidia and their protozoan spores are ingested by the insect. Once within the stomach, they multiply vegetatively in the cytoplasm, gradually spreading throughout the body and causing chronic sickness. A protozoan-infested bug can be easily recognized by its soft body and easily breakable body. Several protozoans are still being exploited for pest management, including *Farinocystis tribolii*, which infects the red flour beetle, *Tribolia castaneum*, with no commercial product available to date. In other countries, one protozoan species, *Nosema locustae* (Fig 4 D), which infects grasshoppers, is being exploited under the trade names "Noloc", "Nolo Bait" and "Semaspore Bait".

The species *Mettaisa frogodermae* was examined and employed within a pest control initiative targeting the khapra beetle. The infective spores exhibit a complete absence of contents. The sporozoites that are in the process of developing become motile within the gastrointestinal tract and subsequently enter the gut to reach the haemocoel, where they proceed to infect cells in vulnerable tissues within a span of two days (Agriinfo.in, 2023). *Vairimorpha necatrix*, formerly known as *Nosema necatrix* and *Thelohania diazoma*, is a microsporidium that has been isolated from at least 14 species of field-collected lepidopteran larvae. *V. necatrix* has been found to infect various species of Lepidoptera, including economically significant agricultural pests such as *Pseudaletia unipuncta, Heliothis zea* and *Heliothis virescens* (Sarwar, 2017a). Additionally, it has been observed to infect *Autographa californica, Trichoplusia ni*, *Spodoptera frugiperda, Spodoptera exigua, Spodoptera ornithogalli* (Sarwar, 2017b), as well as *Plathypena scabra, Pseudoplusia includens* and *Hyphantria cunea*, which have shown potential in controlling the black cutworm *Agrotis ipsilon* (Sarwar, 2019). Moreover, the utilization of *V. necatrix* in the context of cabbage plants infested with *Trichoplusia ni* and *Pieris rapae*, as well as soybeans or sorghum plants affected by the green cloverworm *Plathypena scabra*, yields substantial benefits in terms of safeguarding crop health and productivity.

The list of pests and their biocontrol agents including predators, parasitoids, entomopathogenic microorganisms

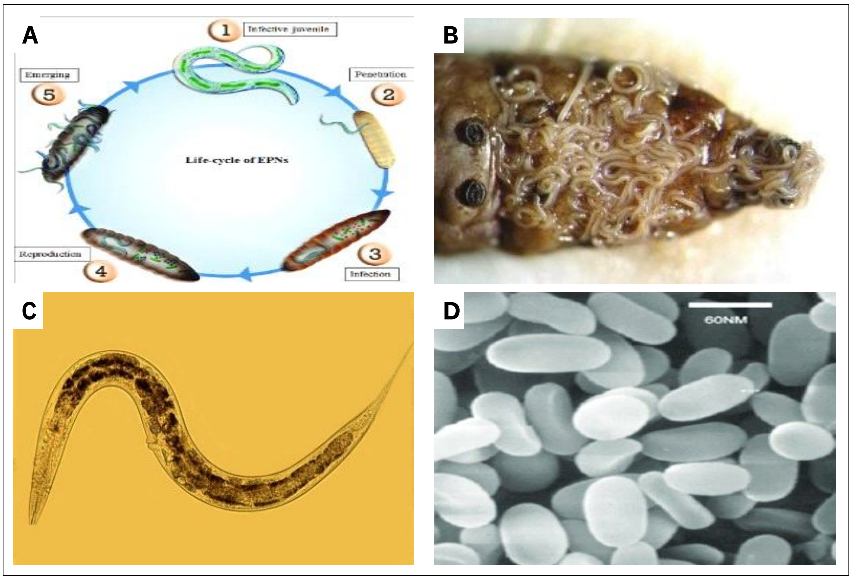

Fig 4: A) Life cycle of an entomopathogenic nematode (Gulcu *et al*., 2017), B) *Steinernema soodi* on *Galleria melonella* (Ali *et al.*, 2005) C) *Rhabditis sp*. (Eisenback, n.d.) D) Spores of *N. locustae* under scanning electron microscopy (Zhang, n.d.).

Table 2: Biological control agents of pests in major tropical vegetable crops (Dhaliwal and Arora, 2016; Reddy, 2018).

Name of the vegetable	Insect pest	Biological control agents: Predators	Parasitoids	Microbial agents and nematodes
Tomato	Aphids	*Aphidoletes aphidimyza* (midge) and *Chrysoperla carnea* (lacewing)	*Aphelinus abdominalis, Aphidius colemani, Aphidius matricariae: Aphidius ervi*	*Verticillium lecanii* and *Beauveria bassiana* (*fungus*)
	White fly	*Macrolophus pygmaeus* (bug),	*Eretmocerus mundus* (specific to *B. tabaci*), *E. eremicus, E. Formosa.*	*Verticillium leccani, Paecilomyces fumosoroseus, Beauveria bassiana*
	Serpentine leaf miner	Lacewings, lady beetles, spiders, fire ants, dragonflies, robber flies and mantids that feed on prey	*Gronotoma micromorpha* (larval and pupal), *Diglyphus sp.* (larval), *Tetrastichus ovularum* (egg),	-
Brinjal	Brinjal shoot and fruit borer	Lacewing (*Chrysoperla carnea*), Mirid bug (*Campyloneura sp.*), lady bird beetles (egg), (*Cheilomenes sexmaculata, Coccinella septempunctata*)	*Bracon greeni* (larval), *Trichogramma chilonis Pristomerous testaceus, Goryphus nursei* (pupal) *etc.*	-
	Aphids	Mirid bugs, anthocorid bugs/pirate bugs (*Orius spp.*), mirid bugs, predatory gall midge, (*Feltiella minuta*), Green lacewings (*Mallada basalis and Chrysoperla carnea*), predatory coccinellids (*Stethorus punctillum*), *etc*.	*Aphidiuscolemani* (adults and nymphs), *Aphelinus spp.* (adults and nymphs) *etc*.	-
	Mites	Anthocorid bugs (*Orius spp.*), mird bugs, syrphid/hover flies, green lacewings (*Mallada basalis* and *Chrysoperla carnea*), predatory mites (*Amblyseius alstoniae, A. womersleyi, A. fallacis* and *Phytoseiulus persimilis*), predatory gall midge (*Feltiella minuta*) *etc*.	-	-
	Leaf hopper	Coccinellids, *Chrysoperla spp.*, mirid bug (*Dicyphus hesperus*), big-eyed bug, (*Geocoris sp.*) *etc*.	*Lymaenon empoascae* (*egg*), *Anagrus flaveolus, Stethynium triclavatum*	-
	Hadda beetle		*Pediobius fovelatus* (Larval endoparasitoid)	*Metarhizium anisopliae* (Green muscardine fungus)
Chilli	Aphids	Anthocorid bugs/pirate bugs (*Orius spp.*), mirid bugs, green lacewings (*Mallada basalis* and *Chrysoperla carnea*), predatory coccinellids (*Stethorus punctillum*) and predatory gall midge, (*Feltiella minuta*)	*Aphidius colemani, Aphelinus spp. etc*.	-

Table 2: Continue...

Table 2: Continue...

	Spider mites and yellow mites	Anthocorid bugs (*Orius spp.*), *Amblyseius ovalis*, mirid bugs, green lacewings (*Mallada basalis)* and *Chrysoperla carnea*), predatory mites (*Amblyseius alstoniae, A. womersleyi, A. fallacis* and *Phytoseiulus persimilis*), predatory coccinellids (*Stethorus punctillum*), predatory gall midge (*Feltiella minuta*) *etc*.	-	*Beauveria bassiana* (entomopathogenic fungus)
	Thrips	*Scolothrips indicus* and *Franklinothrips megalops*	-	*Steinernema feltiae* (nematode)
Bhendi	Shoot and fruit borer	*Chrysoperla carnea*, Coccinellid beetles	*Trichogramma chilonis* (egg), *Tetrastichus spp.* (egg), *Telenomus spp.* (egg), *Chelonus blackburni* (egg larval) *Campoletis chlorideae* (larval), *Goniophthalmus halli* (larval), *Bracon spp.* (larval) *etc*	*Ovomermis albicans* (entomopatogenic nematode)
	White fly	Mirid bug (*Dicyphus hesperus*), (*Geocoris sp.*) *etc*.	*Encarsia sp*., *Eretmocerus sp*., *Chrysocharis pentheus*	-
	Jassids	Chrysopids and coccinellids	-	-
Cucurbits	Cucurbit fruit fly/ Melon fly	-	*Opius fletcheri* (pupal) *etc*	-
	Pumpkin beetle	*Rhynocoris fuscipes*	*Celatoria setosa* (grub) *etc*.	*Steinernema riobravis* (nematode), *Gregarina crenata* (protista),
	Serpentine leaf miner	Lacewings, lady beetle, spiders, fire ants, dragonfly, robber fly, praying mantis *etc*.	*Diglyphus sp.* (larva), *Opius sp.* (pupal) *Chrysocharis sp*., *Neochrysocharis formosa* (Larval) *etc*	-
	Pumpkin caterpillar	-	*Apanteles spp*., *Bracon hebetor, Chelonus sp*., *Campoletis chlorideae, Elasmus brevicornis, Brachymeria lasus, B. margaroniae*	

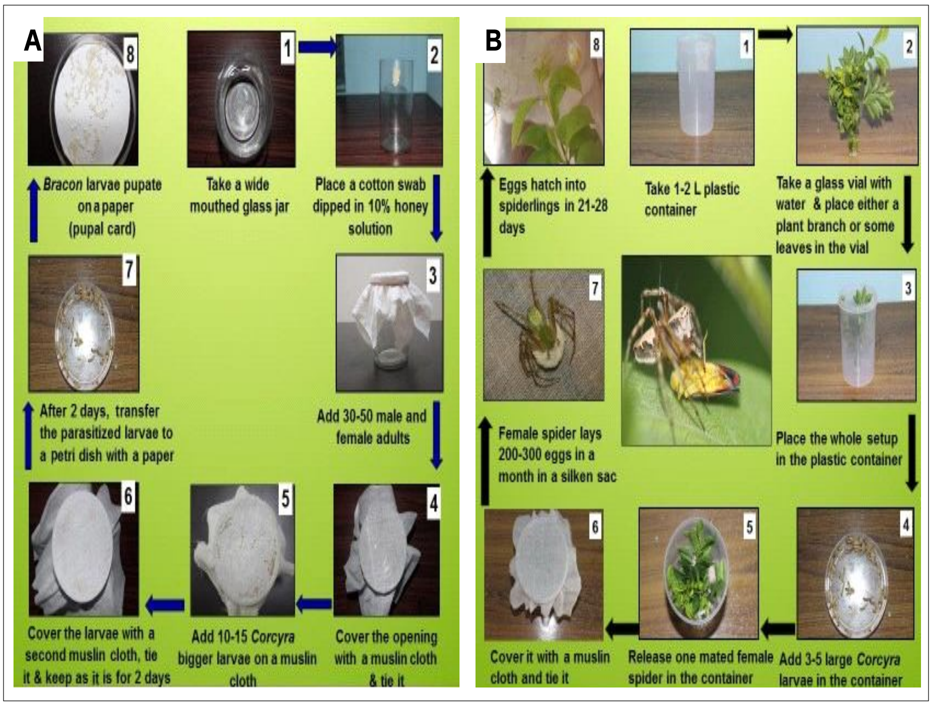

Fig 5: A) Low-cost production technology of Parasitoids *Bracon hebetor* and *B. brevicornis* (tub method) by NIPHM (NIPHM, n.d.), B) Low-cost production technology of spiders by NIPHM (NIPHM, n.d.).

and entomophagous nematodes are mentioned in the Table 2 and are as follows.

Biocontrol agents as commercial biopesticides

Chemical pesticide use in agriculture must be drastically decreased and sustainable biocontrol methods must be pushed. Interest in biological control agents or biopesticides has increased as a result of their ecological benefits (Roger, 2012). On the other hand, their commercialization lags far behind since an acceptable regulatory framework is required for their authorization, commercialization and use. India's growth has been gradual due to insufficient regulation, a lack of capability and the ineffective execution of policies relating to biopesticides and biological control agents (Arjjumend and Koutouki, 2018). This results in a situation where manufacturers and importers of biopesticides and biocontrol agents face different regulatory frameworks and administrative barriers (Arjjumend and Koutouki, 2018). Switching from chemical pesticides to biological agents would also improve the country's environmental and ecological goals. A number of entities, including Indian Council of Agricultural Research (ICAR) institutions and state agricultural universities, are collaborating on biological pest management through an outreach program. These institutes have created a variety of beneficial biocontrol methods for farmers. Additionally, the National Institute of Plant Health Management (NIPHM) has developed low-cost technologies for producing these biocontrol agents (Fig 5 A, B).

The absence of toxic effects, the absence of development of resistance in pests, the absence of poison residues in the soil and rivers, the absence of toxic buildup in the food chain and the absence of the killing of pollinators and predators are all advantages of biological pest control. In addition, it has its own drawbacks, such as being slow to control pests and diseases, being unpredictable, some biocontrol agents being difficult and expensive to create and administer and requiring expert supervision during the handling and application of biocontrol agents.

CONCLUSION

In spite of the fact that vegetables are high-value, low-volume crops, they are susceptible to a wide range of insect pests. They not only reduce yield, but they also diminish product quality. Vegetables are used in a variety of ways, either raw in salads or cooked in a range of dishes. Pesticides are used on vegetable crops at a higher rate than on any other type of crop. With the growing awareness of the detrimental effects of pesticides on the environment and human health, the focus has been shifted toward biological pest management. Biological control of pests in vegetable crops is often regarded as the most effective and long-lasting approach of pest management in the industry. It is essential that the following requirements be met for the successful application of biological control measures in India. They are:

i. The government, the Federation, the commodities and the boards of directors should make every effort to raise public knowledge about the conservation and use of biocontrol agents.
ii. It is necessary to ensure that existing bio-control laboratories of the central and state governments are fully utilized by

providing sufficient staff and resources so that efficiency, productivity and quality may be improved to the desired level.

iii. Governments at all levels, including the federal government, state governments, non-governmental organizations (NGOs) and Krishi Vigyan Kendras (KVKs), should pursue a program of training authorities and farmers with the goal of developing vital human resources in biological management.

iv. It is necessary to develop a low-cost technology for the mass manufacturing of bioagents and biopesticides.

v. It is important to encourage the establishment of biocontrol production facilities at the village level that can be operated by unemployed youth.

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Conflict of interest

The authors declare no conflict of interest.

REFERENCES

Abenaim, L., Bedini, S., Greco, A., Giannotti, P. and Conti, B. (2022). Predation capacity of the banded thrips *Aeolothrips intermedius* for the biological control of the onion thrips *Thrips tabaci*. Insects. 13(8): 702. https://doi.org/10.3390/insects13080702.

Agriculture Post, (2021). How would be the horticulture production in 2020-21? Have a look at advance estimates. Agriculture Post. Accessed: February 27, 2023. Available at: https://agriculturepost.com/allied-sectors/how-would-be-the-horticulture-production-in-2020-21-have-a-look-at-advance-estimates/.

Agriinfo.in (2023). Protozoa in Bio-controls of Crop Pest. Agriinfo.in. Accessed: August 11, 2023. Available at: https://agriinfo.in/protozoa-in-bio-controls-of-crop-pest-777/.

Alam, S.N., Dutta, N.K., Ziaur Rahman, A.K.M. and Sarker, M.A. (2006). Annual Report 2005-2006. Division of Entomology, BARI, Joydebpur, Gazipur. 86.

Alam, S.N., Rashid, M.A., Rouf, F.M.A., Jhala, R.C., Patel, J.R., Satpathy, S., Shivalingaswamy, T.M., Rai, S., Wahundeniya, I., Cork, A., Ammaranan, C. and Talekar, N.S. (2003). Development of an integrated pest management strategy for eggplant fruit and shoot borer in South Asia. Technical Bulletin TB28, AVRDC-The World Vegetable Center, Shanhua, Taiwan. 66.

Ali, S.S., Ahmad, R., Hussain, M.A. and Pervez, R. (2005). Pest management in pulses through entomopathogenic nematodes. Indian Institute of Pulses Research, Kanpur. 59.

Altieri, M.A., Nicholls, C.I. and Fritz, M.A. (2005). Manage insects on your farm: a guide to ecological strategies (No. Handbook Series Book 7). Sustainable Agriculture Research and Education (SARE).

Ansari, M.A., Shah, F.A., Whittaker, M., Prasad, M. and Butt, T.M. (2007). Control of western flower thrips (*Frankliniella occidentalis*) pupae with *Metarhizium anisopliae* in peat and peat alternative growing media. Biological Control. 40(3): 293-297.

APEDA, R.N. (2020). Agricultural and Processed Food Products Export Development Authority.

ARBICO Organics (n.d.). (2023). *Beauveria bassiana*. ARBICO Organics. Accessed: February 25, 2023. Available at: https://www.arbico-organics.com/category/beauveria-bassiana-beneficial-fungal-insect-control.

Arjjumend, H. and Koutouki, K. (2018). Science of biopesticides and critical analysis of Indian legal frameworks regulating biocontrol agents. International Journal of Agriculture, Environment and Biotechnology. 11(3): 579-587.

Asaff, A., Cerda-García-Rojas, C. and De la Torre, M. (2005). Isolation of dipicolinic acid as an insecticidal toxin from *Paecilomyces fumosoroseus*. Applied Microbiology and Biotechnology. 68: 542-547.

Botond, A., Csorba, C., Putnoky-Csicsó, B., Koncz, R., Bandi, A., István, N. and Bálint, J. (2020). Biological control of thrips pests (Thysanoptera: Thripidae) under greenhouse conditions in Transylvania, Romania. DRC Sustainable Future: Journal of Environment, Agriculture and Energy. 1: 147-154. DOI: 10.37281/DRCSF/1.2.7.

Breeding Butterflies.com. (n.d.). (2023). Caterpillars, Eggs and Pairing. Available at: https://breedingbutterflies.com/caterpillars-eggs-pairing/ (Accessed: 30 August 2023).

Castellanos-Moguel, J., González-Barajas, M., Mier, T., Montes, M.R.R., Aranda, E. and Toriello, C. (2007). Virulence testing and extracellular subtilisin-like (Pr1) and tripsina-like (Pr2) activity during propagule production of *Paecilomyces fumosoroseus* isolates from whiteflies (Homoptera: Aeyrodidae). Revista Iberoamericana de Micología. 24: 62-68.

Chakraborti, S. and Sarkar, P.K. (2011). Management of Leucinodes orbonalis Guenee on eggplants during the rainy season in India. Journal of Plant Protection Research. 51(4): 325-328.

Choudhury, M.A., Mondal, M.F., Khan, A.U., Hossain, M.S., Azad, M.O., Prodhan, M.D., Uddain, J., Rahman, M.S., Ahmed, N., Choi, K.Y. and Naznin, M.T. (2021). Evaluation of biological approaches for controlling shoot and fruit borer (*Earias vitella* F.) of okra grown in peri-urban area in Bangladesh. Horticulturae. 7(6): 135. DOI: 10.3390/horticulturae7060135.

Clark, J.K. (n.d.). *Hyposoter exiguae wasp*. Available at https://ipm.ucanr.edu/PMG/S/I-LP-SGUA-HE.009.html (Accessed 23 February 2023).

Cork, A., Alam, S.N., Rouf, F.M.A. and Talekar, N.S. (2003). Female pheromone of brinjal fruit and shoot borer, *Leucinodes orbonalis*: Trap optimization and preliminary mass trapping trials. Bulletin of Entomological Research. 93: 107-113.

Davari, A., Parker, B.L., Sullivan, C.F., Ghalehgolabbehbahani, A. and Skinner, M. (2021). Biological control of Western flower thrips, *Frankliniella occidentalis* using a self-sustaining granular fungal treatment. Bulletin of Entomological Research. 1-6. DOI: 10.1017/S0007485321000365.

Dhaliwal, G.S. and Arora, R. (2016). Integrated Pest Management-concepts and Approaches. Kalyani Publishers, New Delhi. 201-234.

Dong, L.Q., Yang, J.K. and Zhang, K.Q. (2007). Cloning and phylogenetic analysis of the chitinase gene from the facultative pathogen *Paecilomyces lilacinus*. Journal of Applied Microbiology. 103(6): 2476-2488.

Eisenback, J.D. (n.d.). (2023). Rhabditis sp. Available at: https://www.shutterstock.com/image-photo/infection-beauveria-bassiana-insects-zombie-on-168851318/ (Accessed: 22 February 2023).

Elbrense, H., Elmasry, A.M.A., Seleiman, M.F., AL-Harbi, M.S. and Abd El-Raheem, A.M. (2021). Can symbiotic bacteria (*Xenorhabdus* and *Photorhabdus*) be more efficient than their entomopathogenic nematodes against *Pieris rapae* and *Pentodon algerinus* larvae? Biology. 10(10): 999. DOI: 10.3390/biology10100999.

Flint, M.L. and Dreistadt, S.H. (1998). Natural Enemies Handbook: The Illustrated Guide to Biological Pest Control. Oakland: University of California Division of Agriculture and Natural Resources. 3386.

Fragoso, D.F.M., Pratissoli, D., Carvalho, J.R.D., Damascena, A.P., Junior, L.M.D.A., Bueno, R.C.O.D.F. and Túler, A.C. (2019). Capacity for Parasitism of *Trichogramma spp*. in Tomato Fruit Borer under Different Temperatures. Journal of Experimental Agriculture International. 38(5): 1-8.

Gibson, DM., Donzelli, B.G.G., Krasnoff, S.B. and Keyhani, N.O. (2014). Discovering the secondary metabolite potential encoded within entomopathogenic fungi. Natural Product Reports. 31: 1287-1305.

Glare, T., Caradus, J., Gelernter, W., Jackson, T., Keyhani, N., Köhl, J. and Zhang, Z. (2012). Have biopesticides come of age? Trends in Biotechnology. 30(5): 250-258.

Gómez, C., Amaya, I., de la Cruz-Quiroz, R., Rodríguez-Herrera, R. and Aguilar, C.N. (2017). Tenebrio molitor biomass as inducer of lipases and proteases produced by *Paecilomyces fumosoroseus* Biomasa de Tenebrio molitor como inductor de lipasas y proteasas producidas por *Paecilomyces fumosoroseus.* Mexican Journal of Biotechnology. 2(2): 142-150.

Gulcu, B., Cimen, H., Raja, R.K. and Hazir, S. (2017). Entomopathogenic nematodes and their mutualistic bacteria: Their ecology and application as microbial control agents. Biopesticides International. 13: 79-112.

Halder, J., Kushwaha, D., Rai, A., Singh, A. and Singh, B.P. (2017). Potential of entomopathogens and neem oil against two emerging insect pests of vegetables. Indian Journal of Agricultural Sciences. 87(2): 220-224.

Halder, J., Rai, A.B., Kodandaram, M.H. and Dey, D. (2011). *Pediobius foveolatus* (Crowford): A Promising Bioagents against *Epilachna vigitionctopunctata*. In: 28th National Conference on Horti-business Linking Farmers with Market, Dehradun, 28-31 May 2011.133.

Hasan, S., Bhamra, A.K., Sil, K., Rajak, R.C. and Sandhu, S.S. (2002). Spore production of *Metarhizium anisopliae* (ENT-12) by solid state fermentation. Journal of Indian Botanical Society. 8: 85-88.

Hein, K.M., Van Driesche, R.G. and Parella, M.P. (Eds.). (2004). Bio Control in Protected Culture. Ball Publishing, Batavia. 3: 522.

Hodek, I., Honìk, A. and van Emden, H.F. (2012). Ecology and Behaviour of the Ladybird Beetles (Coccinellidae). John Wiley and Sons.

Horstman, J. (n.d.). *Endoparasitoid Braconid wasp*. Available at https://www.flickr.com/photos/itchydogimages/8378397195/sizes/l/ (Accessed 23 February 2023).

Humber, R.A. (2008). Evolution of entomopathogenicity in fungi. Journal of Invertebrate Pathology. 98(3): 262-266. https://doi.org/10.1016/j.jip.2008.02.017.

Kellen, (2018). Green lacewing larva. Available at: https://www.pestwiki.com/lacewing-life-stages/ (Accessed 14 February 2023).

Khan, A., Williams, K.L. and Nevalainen, H.K. (2004). Effects of *Paecilomyces lilacinus* protease and chitinase on the eggshell structures and hatching of *Meloidogyne javanica* juveniles. Biological Control. 31(3): 346-352.

Kodandaram, M.H., Halder, J. and Rai, A. (2014). New insecticide molecules and entomopathogens against Hadda beetle, *Henosepilachna vigintioctopunctata* infesting vegetable cowpea. Indian Journal of Plant Protection. 42: 333-337.

Krishnamoorthy, A. (2012). Exploitation of egg parasitoids for control of potential pests in vegetable ecosystems in India. Comunicata Scientiae. 3(1): 1-15.

Larsson, H. (2017). Ladybug larva. Available at: https://www.istockphoto.com/photo/seven-spot-ladybug-coccinella-septempunctata-larva-feeding-on-aphid-gm658804226-120683621/ (Accessed 14 February 2023).

Mahr, D.L., Whitaker, P., Ridgway, N.M. (2008). Biological control of insects and mites: An introduction to beneficial natural enemies and their use in pest management. University of Wisconsin Cooperative Extension, No. A3842.

Marshall Grain Co. (2022). *Trichogramma chilonis* parasitizing egg. Available at https://www.marshallgrain.com/post/trichogramma-wasps-the-perfect-beneficial-insect/ (Accessed 14 February 2023).

Misra, H.P. (2008). New promising insecticides for the management of brinjal shoot and fruit borer, *Leucinodes orbonalis* guenee. Pest Management in Horticultural Ecosystems. 14(2): 140-147.

Munawar, M., Khan, S.A., Javed, N., Haq, I.U. and Gondal, A.S. (2015). Bio-management of tomato wilt complex caused by *Meloidogyne incognita* and *Fusarium oxysporum f. sp. lycopersici*. Nematology. 17(4): 479-485.

National Horticulture Board, (2018). National Horticulture Data Base. National Horticulture Board. Accessed: February 14, 2023. Available at: http://nhb.gov.in.

National Institute of Plant Health Management. (n.d.). (2023). Low-cost production technology of Parasitoids Bracon hebetor and B. brevicornis (tub method) by NIPHM. Available at: https://niphm.gov.in/mothercultures.html/ (Accessed: 14 February 2023).

National Institute of Plant Health Management. (n.d.). (2023). Low-cost production technology of spiders by NIPHM. Available at: https://niphm.gov.in/mothercultures.html/(Accessed: 14 February 2023).

Nishad, M.K., Kumar, M., Kishor, D.R. and Moses, S. (2019). Population dynamics of brinjal shoot and fruit borer (*Leucinodes orbonalis* Guenée) during the cropping season and its correlation with weather parameters. Journal of Entomology and Zoology Studies. 7(1): 1571-1575.

Orr, D. (2009). Biological control and integrated pest management. Integrated Pest Management: Innovation-Development Process. 1: 207-239.

Ortiz-Urquiza, A. and Keyhani, N.O. (2013). Action on the surface: Entomopathogenic fungi versus the insect cuticle. Insects. 4(3): 357-374. https://doi.org/10.3390/insects4030357.

Patil, P., Behera, S., Ram, R. and Annamalai, M. (2021). Biological control of insect pests in vegetable crops: An eco-friendly approach. International Journal of Current Microbiology and Applied Sciences. 10: 1358-1373. DOI: 10.20546/ijcmas.2021.1001.162.

Péchy-Tarr, M., Bruck, D.J., Maurhofer, M., Fischer, E., Vogne, C., Henkels, M.D., Donahue, K.M., Grunder, J., Loper, J.E. and Keel, C. (2008). Molecular analysis of a novel gene cluster encoding an insect toxin in plant-associated strains of *Pseudomonas fluorescens*. Environmental Microbiology. 10(9): 2368-2386. https://doi.org/10.1111/j.1462-2920.2008.01662.x.

Portal Fruiticola.com. (2018). *Moth larva affected by Bacillus thuringiensis*. Available at https://www.portalfruticola.com/noticias/2018/05/11/el-control-de-insectos-con-bacillus-thuringiensis (Accessed 14 February 2023).

Protasov, A.N. (n.d.). *Weevils infected by Metarhizium anisopliae*. Available at https://www.shutterstock.com/image-photo/entomopathogenic-fungi-beauveria-bassiana-metarhizium-anisopliae-1406151863/(Accessed 22 February 2023).

Qayyum, M., Wakil, W., Arif, M. and Sahi, S. (2015). *Bacillus thuringiensis* and nuclear polyhedrosis virus for the enhanced bio-control of *Helicoverpa armigera*. International Journal of Agriculture and Biology. 17. 10.17957/IJAB/15.0025.

Rai, A.B., Halder, J. and Kodandaram, M.H. (2014). Emerging insect pest problems in vegetable crops and their management in India: An appraisal. Pest Management in Horticultural Ecosystems. 20(2): 113-122.

Raimo. (n.d.). Larvae of ectoparasitoid wasp. Available at: https://www.diptera.info/forum/viewthread.php?thread_ id=72753 (Accessed: 23 February 2023).

Raina, J. and Yadav, G.S. (2018). Brinjal shoot and fruit borer: Bio-ecology and management. Journal of Pharmacognosy and Phytochemistry. 7(4): 444-449.

Raju, S.V.S., Bar, U.K., Shanker, U. and Kumar, S. (2007). Scenario of infestation and management of eggplant shoot and fruit borer, *L. orbonalis* Guenee in India. Resistant Pest Management Newsletter. 16(2): 14-16.

Rao, G.R., Kumar, C.S., Sireesha, K. and Kumar, P.L. (2015). Role of nucleopolyhedroviruses (NPVs) in the management of lepidopteran pests in Asia. Biocontrol of Lepidopteran Pests: Use of Soil Microbes and their Metabolites. 11-52.

Reddy, D.S. (2018). Applied Entomology: For ICAR, JEF, SRF, ARS, SAUs Entrance Exams, UPSC-Civil Services Exams (Prelims and Mains), B. Sc and M. Sc. New Vishal Publications. 131-142.

Roger, C.R. (2012). Trends for Commercialization of Biocontrol Agent (Biopesticide) Products. In: Plant Defence: Biological Control. DOI: 10.1007/978-94-007-1933-06.

Sabbour, M. (2015). Biocontrol of the tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Egypt. Middle East Journal of Agriculture Research. 3(3): 499-503. DOI: 10.13140/RG.2.1.3486.4480.

Saha, M., Sarkar, S., Sarkar, B., Sharma, B.K., Bhattacharjee, S. and Tribedi, P. (2016). Microbial siderophores and their potential applications: A review. Environmental Science and Pollution Research. 23: 3984-3999.

Sampaio, M.V., Bueno, V.H.P., Silveira, L.C.P. and Auad, A.M. (2009). Biological control of insect pests in the tropics. Tropical Biology and Conservation Management. 3: 28-70.

Sanda, N.B. and Sunusi, M. (2014). Fundamentals of biological control of pests. International Journal of Chemical and Biochemical Sciences. 1(6). ISSN: 2349-2724.

Sarwar, M. (2017a). Characteristics of armyworm *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) occurrence and control on cotton. Scholars Journal of Research in Agriculture and Biology. 2(1): 33-38.

Sarwar, M. (2017b). Cotton bollworm *Helicoverpa armigera* (Hubner, 1809) (Lepidoptera: Noc-tuidae) and development of integrated pest management platform. Scholars Journal of Research in Agriculture and Biology. 2(1): 63-70.

Sarwar, M. (2019). Multiple Integrated Pest Management (IPM) and Area-wide Management (AWM) Approaches for Insect Pests of Chickpea *Cicer arietinum* (L.) Walp Crop. In: Handbook of Chickpeas: Nutritional Value, Health Benefits and Management, [Lund, A.T. and Schultz, N.D. (Eds.)]. Nova Science Publishers, Inc., New York. 237-263.

Sharma, S., Kooner, R. and Arora, R. (2017). Insect pests and crop losses. Breeding Insect Resistant Crops for Sustainable Agriculture. 45-66.

Shivalingaswamy, T.M.S., Satpathy, S., Banerjee, M.K. (2002). Estimation of Crop Losses Due to Insect Pests in Vegetables. In: Resource Management in Plant Protection, [Sarat, B.B., VaraPrasad, K.S., Anita, K., Rao, R.D., Chakraborty, S.K., Chandukar, P.S. (Eds.)], Vol. I. Plant Protection Association of India, Hyderabad. (pp. 24-31).

Shivalingaswamy, T.M.S., Satpathy, S., Rai, A.B. and Rai, M. (2006). Insect pests of vegetable crops: Identification and management. Technical Bulletin. 30: 15.

Silva, L.P., Souza, I.L., Marucci, R.C. and Guzman-Martinez, M. (2023). *Doru luteipes* (Dermaptera: Forficulidae) and *Orius insidiosus* (Hemiptera: Anthocoridae) as nocturnal and diurnal predators of thrips. Neotropical Entomology. 52(2): 263-272. DOI: 10.1007/s13744-022-00982-7.

Talibi, I., Boubaker, H., Boudyach, E.H. and Ait Ben Aoumar, A. (2014). Alternative methods for the control of postharvest citrus diseases. Journal of Applied Microbiology. 117(1): 1-17.

Tanga, X.X., Sun, X.L., Pub, G.Q., Wang, W.B., Zhang, C.X. and Zhua, J. (2011). Expression of a neurotoxin gene improves the insecticidal activity of *Spodoptera litura* nucleopolyhedrovirus (SpltNPV). Virus Research. 159(1): 51-56.

The Spruce, (2021). Recognize Lady Beetle (Ladybug) Nymphs. Available at: https://www.thespruce.com/recognize-lady-beetle-ladybug-nymphs-1402696 (Accessed: 30 August 2023).

Trunfio, D. (2019). Ladybug adult. Available at: https://www.greenme.it/ambiente/natura/slavare-insetti-moria/(Accessed 14 February 2023).

Van Lenteren, J.C. (2012). The state of commercial augmentative biological control: Plenty of natural enemies, but a frustrating lack of uptake. Bio Control. 57(1): 1-20.

Vanitha, S.M., Chaurasia, S.N.S., Singh, P.M. and Naik, P.S. (2013). Vegetable Statistics. Technical Bulletin No. 51, IIVR, Varanasi. 250.

Vila, E. (2021). Green lacewing adult. Available at: https://www.plataformatierra.es/innovacion/futuro-control-biologico-retos (Accessed 14 February 2023).

Yang, J., Zhao, X., Liang, L., Xia, Z., Lei, L., Niu, X. and Zhang, K.Q. (2011). Overexpression of a cuticle-degrading protease Ver112 increases the nematicidal activity of *Paecilomyces lilacinus*. Applied Microbiology and Biotechnology. 89: 1895-190

Yasin, M., Qazi, M.S., Wakil, W. and Qayyum, M.A. (2020). Evaluation of nuclear polyhedrosis Virus (NPV) and emamectin benzoate against *Spodoptera litura* (F.) (Lepidoptera: Noctuidae). Egyptian Journal of Biological Pest Control. 30(1): 1-6.

Zhang, L. (n.d.). Spores of *N. locustae* under scanning electron microscopy. Available at https://www.researchgate.net/figure/Spores-of-N-locustae-under-scanning-electron-microscopy-photo-by-Long-Zhang_fig1_350726809/ (Accessed 22 February 2023).

Zhang, Y. (n.d.). Moth larva affected by entomopathogenic fungus (*Beauveria bassiana*). Available at https://www. shutterstock.com/image-photo/infection-beauveria-bassiana-insects-zombie-on-168851318/ (Accessed 14 February 2023).