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Review Article

Exploring the Efficacy of *Beauveria bassiana*: A Comprehensive Review on its Role as a Biocontrol Agent for Insect Population Management in Agriculture

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Abstract

This paper thoroughly investigates the possibilities of entomopathogenic fungus, especially *Beauveria bassiana*, as a feasible and eco-friendly substitute for traditional chemical pesticides under the framework of Integrated Pest Management (IPM). In order to lower the excessive reliance on synthetic agrochemicals, the growing problem of pesticide resistance among pest populations and the related negative consequences on environmental and human health drives increasing need to adopt sustainable pest control practices. In this context, entomopathogenic fungi are an important biological control agent because of their inherent pathogenic features, wide host range and several modes of actions. This fungus not only infects and kills many species of insect pests (chewing and sap-sucking) but also interacting endophytically within plant tissues. Their colonization of the plant may strengthen such resistance and enhances the plant's natural defences, which indirectly reduce pests and increase the resilience of plants. Moreover, the development of innovative formulation technologies in recent years has also enhanced the persistence and field efficacy of *B. bassiana*, allowing its practical usage possible across a wide range of agro-climatic conditions. This fungus, which can be a direct insecticide and cause plant systemic resistance, has several properties that help to reduce reliance on chemical pesticide use. This study has examined the challenges and possibilities of using entomopathogenic fungus and points a way toward the adoption of commercially viable and environmentally sustainable pest control techniques in Indian agriculture and beyond.

Keywords: *Beauveria bassiana*, Biocontrol agent, Entomopathogenic fungi, Pathogenicity, Pest control strategies, *Lecanicillium lecanii*

Introduction

Integrated Pest Management (IPM) includes precise pest identification, comprehensive inspection and focused treatment. This all-encompassing strategy guarantees efficient and long-lasting pest management. Following an examination and pest identification, the treatment (if necessary) is carried out using a pesticide that is particular to the pest and has a short persistence. As a result, IPM considers biological pest management to be a key component. Incorporated pest management includes biological control as a key component (IPM) (Khan *et al.*, 2012). The quest for less chemical inputs in agriculture, insecticide resistance to synthetic insecticides that results in environmental contamination, negative impacts on human health and other creatures and widespread use of chemically synthesized pesticides have all encouraged the creation of alternative pest management methods (Khan *et al.*, 2012). Biological control and use of microbial agents for biological control are attractive options to traditional pesticides since

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they decimate insect populations without endangering human health or the environment. Given the complexity of the method of action of microbial biocontrol agents, it is exceedingly challenging for a pest to become resistant to MBCAs (Khan *et al.*, 2012). MBCAs, which include bacteria, viruses, nematodes and fungus, are successfully and advantageously employed all over the world. However, due to their simplicity in application, enhanced formulation, wide range of known harmful strains, straightforward engineering processes and increased production of native proteins, fungi are the most important of all MBCAs. Moreover, because of their wide host range, mode of disease induction and capacity to attack pests with chewing and sap-feeding habits including mosquitoes and aphids, the entomopathogenic fungi are essential as biological control agents (Khan *et al.*, 2012).

Recent studies have shed light on the several ways *Beauveria bassiana* supports sustainable farming. Apart from its ability to directly infect and kill insect pests, this entomopathogenic fungus also form endophytic connections inside plant tissues that enhance host defence mechanisms. Bahadur (2023) showed that *B. bassiana* produces a variety of metabolites, including insecticidal, antifungal and antibacterial compounds, which support plant defences and encourage development. Similarly, Tomilova *et al.* (2022) found that its endophytic colonization not only greatly lowers pest populations, including aphids and thrips, but also stimulates defensive mechanisms by means of jasmonic acid and salicylic acid pathway induction. Furthermore, Lida *et al.* (2023) also found that using *B. bassiana* activates salicylic acid-mediated pathways that cause a hypersensitive reaction, hence reducing pathogen penetration and therefore suppressing powdery mildew on crops. These results taken together confirm the dual role of *B. bassiana* as both a direct insecticidal agent and an indirect promoter of systemic plant resistance, so qualifying it as a very flexible tool for integrated pest control.

Biological methods for controlling insects emphasize entomopathogens. Managing insect pests by using microorganisms as a kind of biological pest control is the safest and most attractive choice. Entomopathogenic fungi are microorganisms that are heterotrophic, eukaryotic, unicellular or multicellular (filamentous). They can reproduce either sexually or asexually, by spores or a mix of both. Because of their diverse range of hosts, entomopathogenic fungi have the most favourable results out of all options. Their phylogenetic diversity, heterotrophic nature and heterotrophic feeding behaviours are diverse. Every insect is basically vulnerable to specific fatal diseases caused by fungi (Singh *et al.*, 2020). *B. bassiana*, an entomopathogenic fungus, is available for purchase in multiple countries globally as an effective substitute to chemical pesticides for controlling insect pests (Saranraj and Jayaprakash, 2017). Among many other insects, *Beauveria bassiana* has shown potent insecticidal action against *Spodoptera litura*, *Tuta absoluta* and *Helicoverpa armigera*. Greenhouse experiments by Lida *et al.* (2023) found vegetable pest death rates of 80%, highlighting their broad-spectrum effectiveness.

Moreover, Swathy *et al.* (2024) observed that incorporating botanical extracts with *B. bassiana* formulations significantly enhances the fungus's persistence and bioactivity under field conditions. Varieties of this fungus, with a broad host spectrum and being a useful insect killer, have been utilized to fight against harmful pests in farming, invasive species and disease-carrying mosquitoes and ticks that affect humans and animals (Farenhorst *et al.*, 2009; Kirkland *et al.*, 2014). *Beauveria bassiana*, a new model organism, may be utilized to research specific components of fungal development and growth, like interactions between host and pathogen (Bing and Lewis, 1992; Lewis *et al.*, 2009; Wanchoo *et al.*, 2009; Jin *et al.*, 2010).

Optimized formulation strategies have emerged as a crucial factor in enhancing the persistence and field efficacy of *B. bassiana* as a microbial biopesticide. Dannon *et al.* (2020) demonstrated that advanced formulations, such as wettable powders and emulsions, significantly improve fungal stability under field conditions, thereby reducing pesticide resistance and non-target impacts. In parallel, recent research has expanded the role of *B. bassiana* beyond its classical entomopathogenic function. Acheampong *et al.* (2023) found that particular strains of *B. bassiana* can reach more than 90% death under controlled environments against important maize storage pests, hence highlighting its promise in many agro-climatic conditions. Daud *et al.* (2020) backed up these results even more by demonstrating that endophytic colonization in maize improves crop yield as well as pest management. Complementary research by Sinno *et al.* (2021) offered a strong proof that particular *B. bassiana* strains can form endophytic relationships in tomato plants, hence reducing foliar diseases including *Botrytis cinerea* and *Alternaria alternate*, and also encouraging plant growth. Laboratory evaluations by Li *et al.* (2024) corroborated the insecticidal potential of *B. bassiana*, with optimal conditions (25°C and 91-100% relative humidity) yielding mortality rates up to 90% in adult insects and minimal effects on non-target developmental stages, thus reinforcing its integration into pest management programs. In addition to mechanical penetration, *B. bassiana* deploys a sophisticated suite of enzymes and secondary metabolites. Stuart *et al.* (2022) elucidated those secreted proteases, chitinases and lipases facilitate cuticle degradation and internal colonization, while metabolomic analyses have identified bioactive compounds such as beauvericin and bassianolide that suppress host immune responses and further enhance fungal virulence under stress conditions.

The entomopathogenic fungus *Beauveria bassiana* is valued commercially as a natural option to traditional pesticides within an agro-ecosystem (Saranraj and Jayaprakash, 2017). Therefore, the fungus *Beauveria bassiana* is treated as a successful biological substitute for synthetic insecticides, used globally as a mycoinsecticide to combat various insect species (Hajek and St. Leger, 1994; Hajek *et al.*, 2001).

Entomopathogenic Fungi (EPF)

Entomopathogenic fungi (EPF) are frequently found in several environments, exhibiting varying host ranges and serve as biocontrol agents against plant pathogenic fungi, insects and arthropods (Khan *et al.*, 2012). While some entomopathogenic fungi only infect scale insects and whiteflies, like *Aschersonia aleyrodes*, others have a broader range of hosts, with specific isolates being more specialized in targeting pests (Khan *et al.*, 2012). Organisms such as *M. anisopliae* and *B. bassiana* have been applied as tools for managing agricultural pests globally owing to their known ability to infect different insects. Maximum of the EPF species come from the Ascomycota and Zygomycota fungi groups (Khan *et al.*, 2012; Thakur *et al.*, 2021). Historically, there were two categories of ascomycete fungi: the Ascomycota and the Deuteromycota. These fungi have the ability to be saprotrophs that invade the rhizosphere and phyllosphere. They can also be endophytic saprotrophs, hemibiotrophic, necrotrophic of plants, entomopathogenic, or mycoparasites and some have evolved various eco-nutritional strategies (Khan *et al.*, 2012).

Recent investigations have shown that entomopathogenic fungi (EPF) are more successful than mechanical penetration of the insect cuticle. These studies show that EPF release a variety of secondary metabolites actively inhibiting insect immune systems. Research by Stuart *et al.* (2022), for instance, verified that *Beauveria bassiana* produces insecticidal compounds like beauvericin, which greatly enhance its virulence. Furthermore, Swathy *et al.* (2024) have also demonstrated that these fungi are quite adaptable in several agroecosystems, hence highlighting their strength as biocontrol agents. Molecular and biological methods have helped to clarify even more the several aspects of EPF activity. Recent studies have shown that *B. bassiana* produces a variety of secondary metabolites *viz*., beauvericin, oosporein, bassianolide and tenellin, which together increase its pathogenicity by compromising host immune responses and promoting cuticle penetration (Ávila-Hernández *et al.*, 2020).

Potential Myco-Biocontrol Alternatives for Insect Infestations

Beauveria bassiana

It is a filamentous fungus which is defective and belongs to the group of insect diseases known as deuteromycete. There are *Beauveria* strains that do well with specific insect hosts (Sandhu *et al.*, 2012). *B. bassiana* are now being isolated from a wide range of insects which are either important for agriculture or medicine all around the world. At least 49 species of the genus *Beauveria* exist, of that which 22 are pathogenic (Kikankie, 2009). Of the commonly used mushrooms in this genus, *Beauveria bassiana*, the white muscardine mushroom, has the most historical significance. There are species in every phylum of fungi that may reproduce sexually or asexually. Because there are many different types of spores, they have a higher chance of surviving in challenging conditions (Alexopoulos and Mims, 1979; Alexopoulos *et al.*, 1996). It is considered an entomopathogenic fungus because it can be found in many different types of soil and infects various insect species with white muscadine disease. *Beauveria bassiana* is among the most frequently encountered entomopathogenic fungi for a variety of reasons, including its ability to infect each phase of its host's life cycle and a greater host range than other Deuteromycetes, global dispersion (Roberts and Hajek, 1992; St Leger and Roberts, 1997; Bidochka *et al.*, 2000). *Beauveria bassiana* colonies grow slowly and can have colours varying from white to yellow and even crimson. They may also seem powdery or fuzzy. They feature a characteristic denticulate rachis and globose bases. The appearance of the aerial conidia is hyaline, smooth and has thin walls. Depending on the species, they might be oval or spherical and on rare instances, they can also be influenced by cultural influences (de Hoog, 1972; Huang *et al.*, 2002). The great host specificity of several isolates of *Beauveria* sp. is an intriguing characteristic. According to reports, *Beauveria bassiana* reduces the diseases brought on by soil-borne plant pathogens such as Fusarium, Rhizoctonia and Pythium.

Lecanicillium lecanii

The insect-killing fungus and widespread fungus called as *Lecanicillium lecanii* can produce huge epizootics in tropical and subtropical areas including warm and humid climates. This fungus uses a filamentous mycelium to attach to the underside of leaves and feeds on nymphs and adults. In monocultures of vulnerable crops, *Lecanicillium lecanii* was thought to be a significant parasite that led to a drastic reduction in cereal-cyst nematode populations.

Nomuraea rileyi

Entomopathogenic and dimorphic hyphomycete fungus *Nomuraea rileyi* is capable of causing widespread death among various insect species. *N. rileyi* is useful for controlling insect pests since it is host-specific and environmentally safe. However, reports of its mode of infection and development in a range of insect hosts, which includes *Trichoplusia ni*, *Helicoverpa zea*, *Plathypena scabra*, *Bombyx mori*, *etc*., provide valuable insights into its pathogenic mechanisms and potential applications in biological control.

Morphology, Culture and Molecular Characterisation of *Beauveria bassiana*

One-celled conidiogenous cells with small, globose to flask-shaped bodies are found in sympodial to whorled clusters in *Beauveria bassiana* (Saranraj and Jayaparakash, 2017). Hyaline, holoblastic conidia that are transported by an ever-expanding sympodial rachis *Beauveria* is a morphologically distinct genus, however species identification is difficult owing to the absence of considerable behavioural difference and its simple structural makeup. The most crucial morphological trait for identifying species in *Beauveria* is conidia (Saranraj and Jayaparakash, 2017). Species identification has become challenging due to the abundance of new species discovered in *Beauveria*. Few of them physically differ from species that were previously documented in the late nineteenth to mid-twentieth century (Petch, 1926). To evaluate morphological species theories, several *Beauveria* revisionary research have been conducted but it was unable to distinguish species using cultural data.

Because it has been difficult to apply morphological methods to identify species in *Beauveria*, researchers have looked for alternative sources of taxonomic information. In addition to being separated from foods, diseased insects and the interior environment, *Beauveria* is present in plant waste and soil. It is widespread in nature and harbours a variety of insects. Lepidoptera and Coleoptera were affected by *Beauveria densa* isolated from cadavers, but not Orthoptera. From the insect family Scarabaeidae, *Beauveria* was separated (Humber, 1997). A white mould called *Beauveria bassiana* grows in culture. In the majority of widely used cultural contexts, it produces numerous white dry, powdery conidia spores with a unique appearance. Moreover, enhanced molecular techniques, such as multi-locus sequence typing, have refined species delineation in *B. bassiana*, thereby facilitating the selection of highly virulent strains for field applications (Ávila-Hernández *et al.*, 2020).

The conidiogenous cells of *Beauveria bassiana* are small and oval, with a thin apical protrusion known as a rachis. The rachis elongates following the formation of each conidium, reaching its longest extent in a zigzag pattern (Saranraj and Jayaparakash, 2017). *Beauveria bassiana* thrived in the exoskeletons of insect cadavers destroyed by the fungus.

Life Cycle of *Beauveria bassiana*

It is believed that *Cordyceps bassiana* is an anamorph of *Beauveria bassiana*. Infectious diseases caused by endoparasites in insects and other arthropods, the genus Cordyceps and its anamorph *Beauveria* (Nikoh and Fukatsu, 2000). The polymorphic fungus *Beauveria bassiana* has both single- and multi-cellular stages in its life cycle. Taking nutrients from the decomposing materials, *Beauveria bassiana*, a common saprobe, develops as multi-cellar mycelia in soil and decaying plant detritus (St-Germain and Summerbell, 1996). Asexual spores known as conidia are created for the function of reproduction and the dissemination of progeny. Conidiogenic cells arise in a zigzag pattern from mycelia hyphae to generate conidia (Saranraj and Jayaprakash, 2017).

Conidia discharged into the environment stay dormant or non-vegetative in the absence of the right germination circumstances. Humidity has a crucial role in conidia activation independently of the host (Boucias and Pendland, 2008). Additionally, germination is aided by the conidia's attachment to the exoskeleton of an insect host (Saranraj and Jayaprakash, 2017). Because of their hydrophobicity, *Beauveria bassiana* conidia are believed to first cling to the host exoskeleton because they make a strong bond with the waxy covering or chitinous surface of the host (Holder and Keyhani, 2005).

A hyphal structure known as a germ tube emerges during the germination phase. The breakdown of cuticle by enzymatic digestion and mechanical exoskeletal component rupture occurs due to the growth of germ tube along the cuticle's surface (Saranraj and Jayaprakash, 2017). *In vivo* blastospores, single-celled morphotypes produced by the fungus after it has gone through the exoskeleton and entered the hemolymph. Elongating hyphae are produced by the blastospores as they consume the nutrients in the hemolymph. These hyphae multiply until they emerge from the insect carcass and start to produce conidia. The outcome is a fuzzy, white insect corpse that has been mummified (Saranraj and Jayaprakash, 2017).

Pathogenicity of *Beauveria bassiana*

The fungal pathogen infection of insects involves four stages: host-fungi contact, spore attachment and germination, cuticle or gut wall penetration leading to tissue invasion and ultimately animal death due to trachea and circulatory system blockage alongside toxin production (Saranraj and Jayaprakash, 2017). In addition to these stages, the pathogenic process is augmented by a series of enzymatic actions. Specifically, *B. bassiana* secretes a suite of cuticle-degrading enzymes, such as proteases, chitinases and lipases, which facilitate rapid cuticle degradation (Stuart *et al.*, 2022). Moreover, metabolomic investigations by Bahadur (2023) have shown that secondary metabolites produced during later stages further disrupt host metabolism, contributing to a swift and effective pathogenic response.

The pathogenic cycle must be completed by saprophytic fungal growth after the host has died. Conidia stick to the host's exoskeleton and they begin to germinate and break through the cuticle through the germ tube to begin the process of fungal pathogenesis. Finally, the fungus grows within the body of the host, leading to the death of the insect host. Under favourable environmental conditions, fungal external sporulation occurred after death (Moore and Prior, 1997).

Insects become infected with entomopathogenic fungus after conidia/ spores germinate on the exoskeleton and penetrate through the integument (Clarkson *et al.*, 1998). The two major sites of infection were the head and the anal region and the larval gut was the most favoured site for fungal growth (Miranpuri and Khachatourians, 1991). *Beauveria bassiana*'s hyphal bodies create hyphae, which eventually pierce the procuticle and reach the hemocoel (Hajek and St. Leger, 1994; Hajek *et al.*, 2001). The blastospores, which are also called as hyphal bodies, are single-nucleated organisms or multi-nucleated organisms without a cell wall, although they do have a thin fibrillar layer and plasma membrane. New hyphae are produced by them, which will eventually occupy the body cavity and keep inactive spores within the decomposed host.

Mode of Action of *Beauveria bassiana*

Beauveria species invade their insect hosts through the skin, just as other entomopathogenic fungus. The following steps help compensate the infection pathway: (1) bonding the spore to the insect cuticle; (2) spore germination on cuticle; (3) penetration through cuticle; (4) evading host immune response; (5) proliferation within the host; and (6) saprophytic outgrowth from the deceased host and generation of new conidia (Maulenova, 2018; Figure 1).

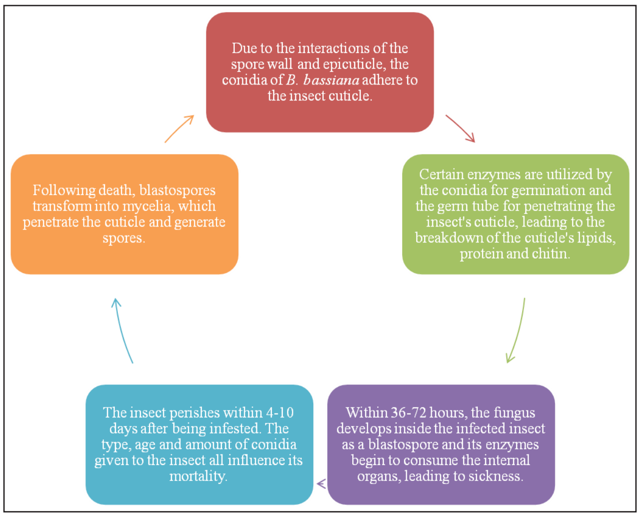

Figure 1: *B. bassiana*'s infection cycle

Spore germination and effective infection of *Beauveria bassiana* depend on a number of variables, which includes the susceptible host, host stage and specific ecological variables including temperature and humidity. *B. bassiana* conidia often begin to germinate after around 10 hours and finish in 20 hours at 25 °C. Once within non-sclerotized cuticle regions including joints, mouthparts and spaces between segments, the germinated spore releases extracellular proteases and chitinases that enable hyphal penetration by break down of proteinaceous and chitinous components. After successfully penetrating, the fungus spreads to other insect host tissues, where it produces deadly secondary metabolites and undergoes significant vegetative development, finally killing the host.

Beyond simple physical penetration, *B. bassiana* uses advanced molecular mechanisms to undermine host resistance. By producing immunosuppressive proteins that significantly lower hemocyte activity, it therefore suppresses key components of the insect immune response (Stuart *et al.*, 2022). Working in tandem with several toxins including bassianolide, beauvericin and tenellin, these proteins not only expedite the breakdown of the insect cuticle but also intricately control immunological signalling pathways. Wang *et al.* (2021) thoroughly examined these diverse secondary metabolites, highlighting their dual function in both enabling entrance and compromising host immunity, hence accelerating systemic collapse in the insect host. Furthermore, recent scanning electron microscopy research has shown that endophytic strains of *B. bassiana* produce higher amounts of extracellular enzymes, including lipases, proteases and chitinases, which further promote cuticle breaching by synergistic action (El-Maraghy *et al.*, 2023). These toxin- and enzyme-mediated approaches offer promising goals for genetic improvement meant to raise the biocontrol effectiveness of this entomopathogenic fungus.

Significance of *Beauveria bassiana* in Agriculture

Agriculture pests continue to be a notable issue and significantly reduce output. Chemical insecticides like DDT and endosulfan have historically been employed to get rid of pesky insects; but on the other hand, chemical pesticides have resulted in a number of issues. As insects develop tolerance to chemical poisons, they decrease their efficacy, which calls for more dosages. Commonly used insecticides harm non-target organisms including beneficial insects like pollinators and the natural enemies of the target insect-pest.

Beauveria bassiana, which may be found all over the world, is the most common species isolated from insects and soil samples, where it may remain in saprogenesis for a long period of time. *B. bassiana* has a wide range of genetic variants that are connected to host and geographic location and differ greatly in their ability to cause diseases. The fungus germinates within 12 to 18 hours of the tegument becoming infected spontaneously, depending on the availability of resources like glucose, chitin and nitrogen (Alves, 1998; Alves *et al.*, 2005). The spores are applied to harmed crops as an insecticide as a wettable powder or emulsified solution. It is categorised as a non-selective biological insecticide due to a wide variety of arthropod hosts on which it parasitizes. *B. bassiana* also preys on green leafhoppers, pine caterpillars and the European corn borer *Ostrinia nubilalis* N.sp. *Nephotettix* (Sandhu *et al.*, 2012).

Beauveria bassiana demonstrated to reduce diseases of soil-borne plant pathogens, such as Pythium, Rhizoctonia and Fusarium *in vitro*. It has also been shown to colonise endophytically in a variety of plants, hinder the growth of plant pathogenic fungi and induce systemic resistance when pathogens infect the plant (Ownley *et al.*, 2010). Research organisations in Honduras, Brazil, Mexico and India among others examined *Beauveria* as an effective deterrent to the coffee berry borer (Fernandez *et al.*, 1985; Haraprasad *et al.*, 2001). *Beauveria bassiana* and *Paecilomyces farinosus* were used in the soil, to drastically decrease the population of *Leptinotarsa decemlineata* (Bajan *et al.*, 1973).

Agricultural pests pose a threat to human society's ability to produce resources and are a direct threat to human health. The capacity of *Beauveria bassiana* to suppress arthropod disease vectors reduces the spread of diseases spread by these insects. Additionally, *Beauveria bassiana* could be helpful in the fight against malaria. Although there are presently no malaria vaccines available, research has shown that fungus-based entomopathogens may be able to limit the disease's transmission (Blanford *et al.*, 2005; Scholte *et al.*, 2005).

Recent studies underscore the potential of optimized commercial formulations of *Beauveria bassiana* in enhancing pest management efficacy. Chouikhi *et al.* (2022) demonstrated that elevated concentrations of *B. bassiana* significantly curtailed egg hatchability and reduced larval survival rates of *Tuta absoluta*, a major pest in tomato production. In parallel, local isolates identified by Islam *et al.* (2023) have exhibited enhanced performance under native environmental conditions, inducing substantial mortality and developmental abnormalities in target species such as *Spodoptera litura*.

In addition, Li *et al.* (2024) provided a quantitative framework for evaluating the virulence of *B. bassiana* by measuring lethal concentration (LC50) and lethal time (LT50), thereby offering critical insights into its practical application under field conditions. Their results support the inclusion of improved fungal formulations into agricultural protection strategies since they can optimize pest control and reduce effects on non-target species.

Oil-based emulsions and nanoencapsulation technologies among other formulation technology developments have significantly increased the shelf-life and field efficacy of *B. bassiana*. For example, Dannon *et al.* (2020) found that such formulations increase conidial viability on leaf surfaces, resulting in a 30-40% reduction in pest death; whereas Tomilova *et al.* (2022) showed that microencapsulation greatly improves UV protection, therefore prolonging the duration of efficient biocontrol.

Influence of Combining Entomopathogens with Other Microorganisms

In agricultural ecosystems, diseases and insect pest damage that results in decreased soil fertility across the world pose significant threats to output and production. It has been noted that repeated exposure to the same biopesticides causes insect pests to develop resistance (Thakur *et al.*, 2021). According to Steinhaus (1951), the combination of the polyhedrosis virus with the entomopathogenic bacterium *Bacillus thuringiensis* can greatly reduce the number of alfalfa caterpillars. Ansari *et al.* (2008) discovered that EPF (*Metarhizium anisopliae* CLO 53) and EPNs (*Steinernema glaseri* and *Heterorhabditis megidis*) have been shown to interact with one another to combat *Hoplia philanthus* larvae (third instars). They discovered that applying these entomopathogens together results in noticeably more larval mortality.

Vega *et al.* (2012) reported the utilizing the nematode *H. bacteriophora* in conjunction with the fungi *B. bassiana* and *M. anisopliae* to combat *Phyllophaga vetula* larvae has significantly increased mortality. Wu *et al.* (2014) discussed the impact of combination of entomopathogen doses on *Cyclocephala lurida* (third instar larvae). Imperiali *et al.* (2017) examined the impact of combining Pseudomonas bacteria, entomopathogenic nematodes (EPNs) and arbuscular mycorrhizal fungus (AMF) affects *Oscinella frit* on wheat plants. In order to reduce the population of mosquitoes (*Aedes aegypti*), Noskov *et al.* (2019) used pathogenic fungus in addition to microbial metabolites. Combining these chemicals has been shown to have a synergistic effect on the death of mosquitoes.

Its combination with other biocontrol agents significantly increases *Beauveria bassiana*'s effectiveness. Recent studies showed that the synergistic interactions between *B. bassiana* and other entomopathogenic fungi and microbial consortia not only increase pest death rates but also reduce reliance on chemical pesticides (Islam *et al.*, 2023). Furthermore, studies now indicate that including *B. bassiana* into thorough integrated pest management (IPM) strategies shows great potential. For example, Dannon *et al.* (2020) developed a cotton IPM model that coupled regular applications of *B. bassiana* with pheromone traps and resistant cultivars, therefore reducing pest occurrence by 65%. Lida *et al.* (2023) also highlighted its possibilities in organic agriculture as its low residue and minimal negative impact on non-target species help to more sustainable agro-ecosystem.

Advantages and Disadvantages of Entomopathogenic Fungi

Advantages

1. Formulation technology developments include oil-based emulsions and encapsulating methods have greatly increased the shelf-life, ultraviolet (UV) tolerance and field persistence of *B. bassiana* conidia. These developments improve its efficacy under various environmental conditions, hence increasing pest death rates (Dannon *et al.*, 2020; Tomilova *et al.*, 2022).

2. Apart from its direct insecticidal qualities, *B. bassiana* shows endophytic potential that promotes triggered systemic resistance and improved plant development. This dual role promotes general plant health as well as pest control (Bahadur, 2023; Tomilova *et al.*, 2022; Lida *et al.*, 2023). The several ways of infection of the fungus also let it be used for a long time in pest control plans, hence lowering the probability of resistance formation in insect populations.

3. Among several agricultural pests, including Lepidopteran larvae, aphids and thrips, *B. bassiana* is quite successful. Including it in integrated pest management (IPM) strategies lets many pest groups be controlled at once. Its wide degree of selectivity is especially important since it reduces damage to non-target helpful species including parasitoids and predacious insects (Lida *et al.*, 2023).

4. *B. bassiana* is particularly appropriate for organic and sustainable agricultural systems because of its ecological specialization and low influence on non-target species. It lowers dependence on artificial insecticides and offers minimal risks to environmental and animal health (Dannon *et al.*, 2020).

5. By means of customized strain development, *B. bassiana* offers significant opportunities for genetic and molecular research meant to improve its virulence, environmental resilience and formulation efficiency.

6. Using *B. bassiana* as a biocontrol agent helps to significantly reduce the application of chemical pesticide, therefore reducing the environmental impact of methods for protecting crops.

Disadvantages

1. Unlike chemical insecticides that can kill insects in a few hours, *B. bassiana* usually needs 2-3 weeks to do so. Under high infestation pressure, this delayed impact could restrict its appropriateness in circumstances requiring rapid insect-pest control.

2. Environmental factors, especially temperature, humidity and UV radiation exposure, greatly affect the efficacy of *B. bassiana*. Unless improved formulations are used, suboptimal circumstances can significantly impede fungal virulence and survival (Stuart *et al.*, 2022; Swathy *et al.*,

2024). Since the pathogenic process is biologically driven, it needs particular environmental conditions for best operation, including appropriate temperature ranges, adequate humidity levels and regulated light exposure.

3. Inconsistent performance might result from strain-to-strain variation and variations in host specificity, which calls for thorough strain selection and local field validation.

4. Though controlled formulations can increase the efficacy of *B. bassiana*, their production and development usually entail significant expenses. Especially in resource-limited agricultural systems, these higher expenses could impede widespread adoption and large-scale commercialization.

5. Preventive therapy is challenging since the pathogen must first be present in order to be administered in a beneficial way.

6. Lack of perseverance and low rate of infection in challenging environmental conditions.

Conclusion

The constantly expanding human population has an increased need for food and fibre from the agricultural land, which is getting less. Though modern agriculture has mostly succeeded in achieving these goals, the use of high yielding varieties, sophisticated irrigation systems and more agrochemicals over the last two to three decades has caused crop losses from diseases, insect pests and weeds.

Recent studies have confirmed the several possibilities of *Beauveria bassiana* in sustainable farming. Its great effectiveness against a broad range of insect pests, including those harming stored items, leaves and stems, has been shown by laboratory and field tests (Daud *et al.*, 2020; Acheampong *et al.*, 2023). Complementary biochemical studies have shown the major involvement of extracellular enzymes and secondary metabolites in increasing the pathogenic capacity of this entomopathogenic fungus (Ávila-Hernández *et al.*, 2020; El-Maraghy *et al.*, 2023). Furthermore, under region-specific environmental circumstances, the adoption of regionally adapted isolates has been demonstrated to enhance pest control (Islam *et al.*, 2023).

Building on these insights, recent studies have further emphasized the potential of *B. bassiana* as a multifunctional biocontrol agent. For example, Bahadur (2023) and Swathy *et al.* (2024) found that in less than ideal environmental circumstances, optimized formulations can maintain the effectiveness of the fungus. Its endophytic colonization of host plants has also been linked to improved plant development and resistance. These dual roles *viz*., efficient pest management and plant growth promotion, emphasize the important contribution of *B. bassiana* in enhancing agro-ecosystem sustainability under growing environmental challenges.

Unlike traditional pesticides, entomopathogenic fungi are less harmful to non-target species and provide a safer choice for application in integrated pest management (IPM). Most of the entomopathogenic fungi are most successful when total pest eradication is not necessary. They therefore appear to play a crucial part in order to accomplish sustainable pest management, in IPM and additional resource improvisation would be beneficial.

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