Review of the potential of *Beauveria bassiana* as a biological controller of pathogens in agricultural crops

Raúl Alberto Cuervo-Mulet[1], Ramón Arturo Reyes-Silva[2*], Sabdi Berzabet Velázquez-Santizo[2], Maira Julieth Borja[3], Claudia Asceneth Castañeda[4]
Universidad de San Buenaventura Cali[1]
Licenciatura en Biología. Universidad de Ciencias y Artes de Chiapas[2]
Ingeniería Agroindustrial. Universidad de San Buenaventura Cali[3]
Institucion Universitaria Antonio José Camacho[4]
*e-mail: ramon.reyess@e.unicach.mx

Resumen
Los hongos entomopatógenos, a menudo considerados únicamente como patógenos de insectos, desempeñan funciones adicionales en la naturaleza, incluidos el endofitismo, el antagonismo de las enfermedades de las plantas y la promoción del crecimiento de las plantas. Estos roles permiten brindar oportunidades para el uso múltiple de estos hongos en estrategias de manejo integrado de plagas (MIP). Este artículo revisa los avances más recientes en el uso del hongo entomopatógeno *Beauveria bassiana*, su control en insectos plaga y en la colonización endofítica de diferentes plantas hospedantes. También aborda los posibles mecanismos de protección conferidos por *Beauveria bassiana* como hongo entomopatógeno y como hongo endófito y explora el uso potencial del mismo en el control biológico dual. Finalmente, se resumen las limitaciones actuales y las direcciones que debería tener las investigaciones futuras con respecto a *Beauveria* spp. como agente de control biológico dual.

Palabras Claves: *Hongos endófitos, Hongos entomopatógenos, Plagas, Biocontrolador, PGP, Beauveria bassiana.*

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Abstract
Entomopathogenic fungi, often considered only as insect pathogens, perform additional functions in nature, including endophytism, antagonism of plant diseases and promotion of plant growth. These roles allow opportunities for the multiple use of these fungi in integrated pest management (IPM) strategies. This article reviews the literature currently available on the entomopathogenic fungus *Beauveria bassiana*, its control in insect pests and in the endophytic colonization of different host plants. It also addresses the possible protection mechanisms conferred by *Beauveria bassiana* as an entomopathogenic fungus and as an endophytic fungus and explores its potential use in dual biological control. Finally, we summarize the current limitations and directions that future research should have regarded *Beauveria spp.* as a dual biological control agent.

Key Words: *E*ndophyte fungus, Entomopathogenic fungus, Pests, Biocontroller, PGP, *Beauveria bassiana*.

Introduction

The applications of *B. bassiana* are broad in Integrated Pest Management (IPM), as they can encompass fields ranging from agriculture (Ranesi et al., 2024; Afandhi et al., 2023; Iida et al., 2023), food production (Amobonye et al., 2022; Gutiérrez-Román et al., 2022) and even the field of medicine, through the control of vector insects that transmit diseases to the population (Pirmohammadi et al., 2023; Tawidian et al., 2023; Vivekanandhan et al., 2022).

Many species of the genus *Beauveria* are morphologically similar, leading to the formation of complexes such as the *B. bassiana* complex and the *B. subscarabaeidicola* complex, which are composed of species such as *B. subscarabaeidicola*, *B. songmingensis*, *B. polyrhachicola*, *B. caledonica*, *B. blattidicola*, among others (Wang et al., 2022), the most notable advantages these fungi offer to plants are protection against endophytic pathogens such as bacteria and phytopathogenic fungi, such as *Fusarium, Epicoccum sp., Alternaria burnsii,* (Pachoute et al., 2024), *Botrytis cinérea* (Sui et al., 2023), etc. *B. bassiana* it is a generalist entomopathogenic fungus that initiates its cycle by penetrating the hard chitinous cuticle of insects, producing secondary metabolites directly in the hemocoel, which causes the death of the insect (Pedrini, 2022).

Aspects such as host compatibility and severe environmental variations can lead to a loss in the viability of fungal conidia (Quesada-Moraga et al., 2024); this is why it is necessary to standardize the processes for the mass production of entomopathogenic fungi as biocontrol agents (Jaronski, 2023).

Entomopathogenic fungi like *B. bassiana* research has been mainly directed to develop them as biological control agents for insects, the great potential of this fungus in pest control has been widely demonstrated (Swathy et al., 2024; Liu et al., 2023; Pirmohammadi et al., 2023; Tawidian et al., 2023; Wakil et al., 2023; Chouikhi et al., 2022; Idrees et al., 2022; Vivekanandhan et al., 2022; Wang et al., 2022; Zhang et al., 2022), even though it is effective on its own, it has been found that symbiosis with bacteria such as *Pseudomonas spp.*, promotes the vegetative growth of the fungus, accelerating the mortality of infected insects (Liu et al., 2023).

Although its most common use is as a biopesticide (Pedrini et al., 2024), it is considered a potential source of research from the metabolomics and transcriptomics perspective, which will allow the identification of metabolites synthesized by the fungus, potentially useful in numerous aspects across various fields of knowledge (Fei et al., 2024).

This article reviews the available literature on the potential of the entomopathogenic fungal *Beauveria spp.* as biological pest insect controller and its endophytic colonization in different plants, The European Commission has recently published a report on the impact of the Community's agricultural policy on the Mediterranean. In addition, it describes the control mechanisms used by fungal entomopathogen as pest insect controller and diseases of agricultural plants and discusses the interactions of *Beauveria spp.* as endophyte with other endophytes. Finally, current research and future research direction to potentially use *Beauveria spp*. as a dual biological control agent are discussed and concluded. For this reason, a review divided by item is presented below about the *Beauveria spp.* as a dual biological control agent in agricultural crops.

Beauveria spp. and biological pest control insects

The cosmopolitan species of *Beauveria* are particularly suitable as possible biological control agents for insect pests, this is because its range of hosts is extremely diverse, can be produced in mass easily and has an extraordinary mechanism in the process of pest insect infection (Blond et al., 2018).

Among the research known is the colonization of *B. bassiana* allowed the reduction of damage caused by trappers and lepidoptera stems in corn (Bruck & Lewis, 2002), Banana Gorgon (Luo et al., 2015; Akello et al., 2008), the fruit worm of the tomato *Helicoverpa zea* (Abdul et al., 2015), the cutting ant *Atta cephalotes* (López & Orduz, 2002), the corn stalk sweeper *Sesamia nonagrioides* (Verma,

2014), the onion thrips, the cotton worm (Castillo & Sword, 2015), among others.
Additionally, the control exerted on insect species that damage tea crops has been demonstrated (Bhattacharyya et al., 2023). To prevent resistance to insecticides, it has been opted to use a combination of insecticide doses with *B. bassiana* doses in both field and laboratory conditions. As mentioned by Wakil et al. (2022), they used concentrations of fipronil with *B. bassiana* to test its insecticidal effect on beetles such as *Rhyzopertha dominica*, *Tribolium castaneum*, *Sitophilus granaries*, and *Trogoderma granarium*, obtaining higher mortality in formulations with fipronil and *B. bassiana*, temperature influenced the results, as the highest mortality was reached at 30°C, with *R. dominica* being the most susceptible. On the other hand, *B. brongniartii* has also been tested for the control of two hemipterans, *Rhopalosiphum padi* and *Sitobion miscanthi*, which damage wheat crops in China, causing high mortality starting from day three in both larvae and adults (Tian et al., 2024).

Coffee (*Coffea arabica*) has been threatened by diseases such as coffee berry borer caused by the beetle *Hypothenemus hampei*, in which infected fruits were treated with *B. bassiana*, achieving 100% mortality (Krutmuang et al., 2023). The potato (*Solanum tuberosum*) crop is also affected by pest insects, with the most important being *Phthorimaea operculella*, a moth that feeds inside the plants, making its control difficult. Good results have been obtained in controlling this insect using potato plants infected with *B. bassiana* (Eltair et al., 2024; Zhang et al., 2023a; Zhang et al 2022). From a different perspective, highlighting the entomopathogenic characteristic previously mentioned of the fungus, the mycoproteins of *B. bassiana* can be derived from a substrate composed of insects such as *Eurysacca melanocampta* and *H. hampei*, transforming them into more proteins for utilization in the food industry (Gutiérrez-Román et al., 2022).

There are studies that test the larvicidal activity using the metabolites directly produced by *B. bassiana*. An example is the metabolites extracted from the fungus against *Tuta absoluta*, causing 80% mortality at 24 and 48 hours after treatment with these compounds (Vivekanandhan et al., 2024). It has been shown that the metabolites α-solanine, 5-O-caffeoylshikimic acid, clerodendrin A, and peucedanin have insecticidal activity, as plants infected with *B. bassiana* overexpress these metabolites, providing protection to tomato plants against *Bemisia tabaci* (Wang et al., 2023).

Mechanism of action

The development of *Beauveria* disease towards the insect pest is divided into three phases: (1) adhesion and germination of the spore of the entomopathogenic fungus in the cuticle of the insect, (2) hemocele penetration and (3) hemocele replication (Jaber & Alananbeh, 2018; Guesmi-jouini et al., 2014; Krasno et al., 2014) (Figure 1).

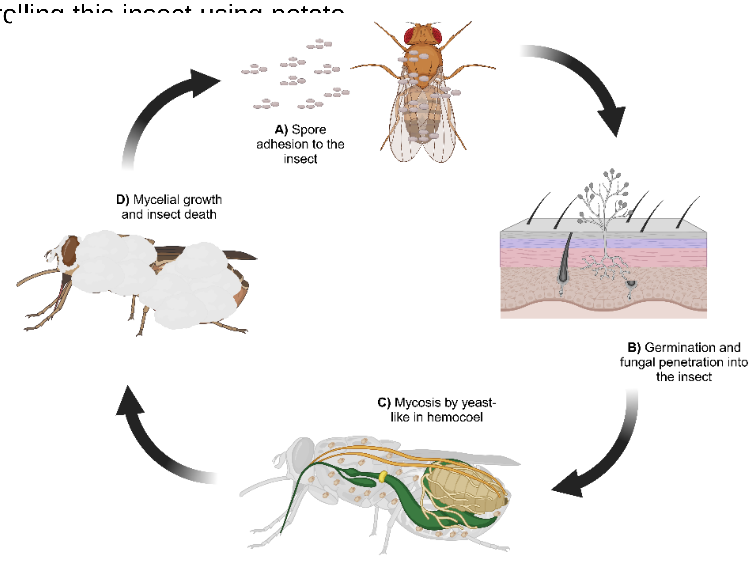

Figure 1. Development of *B. bassiana* in insects. (Jaber & Alananbeh, 2018; Guesmi-jouini et al., 2014; Krasno et al., 2014).

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(1) Adhesion and germination of the spore
After the spores have been dispersed by biotic or abiotic factors, they can enter the insect through the mouth, spiracles, anus, or its surface. Once attached, a set of enzymes is released to infiltrate the insect. (Altinok et al., 2019). Germination (Figure 1) is a process by which a spore emits one or more small germinative tubes that, as they grow and lengthen, give rise to hyphae, this process depends on the conditions of humidity and ambient temperature. The success of germination and penetration does not depend on the percentage of germination but on the time of the duration of germination, the mode, aggressiveness of the fungus, type of spore and host susceptibility (Guesmi-jouini et al., 2014).

(2) Penetration into the hemocele
The penetration process is possible thanks to a combination of physical and chemical mechanisms. The physical mechanism is given by the pressure exerted by the haustory which first deforms the cuticular layer then breaking up the sclerosed and membranous areas of the cuticle (Figure 1). The chemical mechanism consists, on the other hand, in the enzymatic action mainly of hydrolytic activities such as protease, lipase and chitinase, which degrade the tissue in the area of penetration facilitating the entrance of the fungus; another mechanism used by fungal entomopathogens such as *Beauveria* to penetrate the hemocele is the oral cavity, spiracles and other external openings of the insect. (Jaber & Alananbeh, 2018).

(3) Replication in the hemocoel
When the spores of entomopathogenic fungi reach the hemocele, most of them make a dimorphic transition from mycelium to yeast. Mycosis induces abnormal physiological symptoms in the insect such as convulsions, lack of coordination, altered behaviors and paralysis. Death occurs due to a combination of effects including physical tissue damage, toxicosis, dehydration of cells by loss of fluid and nutrient consumption (Quiroz et al., 2008). Also, it has been observed that to prevent the attack of the insect's immune system, fungi often do without cell wall formation and develop as protoplasts, avoiding recognition by circulating hemocytes in the hemocele, when the nutrients from the insect, particularly the nitrogen sources, become depleted, the yeast-like phases resume their mycelial growth (Figure 1) (Krasno et al., 2014).

Beauveria and its function as a benefical endophyte

The term endophyte refers to microorganisms that colonize the interior of plant tissues without causing apparent damage to host plants. Endophyte fungi have been found in all types of plants, from those living in the arctic to the tropics, as well as in agricultural fields (Sánchez-Fernández et al., 2013). One of the main investigations on the introduction of the entomopathogenic fungus *Beauveria* is presented by Lewis and Cossentine in 1986; where *B. bassiana* was established as an endophyte after aqueous application to the maize plants *Zea may L*. (Poaceae), for the suppression of the European corn sweeper *Ostrinia hubialis* (Hübner) (Lepidoptera: pyradilae) throughout the season (Verma, 2014).

B. bassiana has been extensively studied for the symbiosis it forms when infecting hosts of agro-industrial importance, thus improving their performance. An example of this is the increased size of tomatoes (*Solanum lycopersicum*), which are larger in plants colonized with *B. bassiana* than in plants without the fungus (Sui et al., 2023). Similarly, it has been tested in melon (*Cucumis melo*) and strawberry (*Fragaria sp.*) crops, even achieving infection rates of 100% in tissues of both pot and field crops, providing resistance against pests such as moths, mites, hemipterans, among others (Mantzoukas et al., 2022). Other investigations where *B. bassiana* has been reported as endophyte are that of (Guesmi-jouini et al., 2014) where it was shown that ten days were sufficient to confirm that *B. bassiana* could be established endophytic in the artichoke *Cynara scolymus.* In sugarcane, *B. bassiana* was shown to endophytically colonize this agricultural plant and improve root establishment (Kasambala et al., 2018).

Beauveria spp. has also been shown to have dual biological control in the bean, naturally occurring in soil and plant; allowing the control of the insect *Piezodorus guildinii* and as a natural endophyte of the common bean plant *Phaseolus vulgaris* (Ramos et al., 2017). On the other hand, (Castle & Sword, 2015) provided evidence that *B. bassiana* and *Metharizum brunneum* can effectively inhibit the growth of several *Furasium* species that cause root rot in cotton plants and (Greenfield et al., 2016) demonstrated that *B. bassiana* and *M. anisopliae* can control the disease causing whitefly *Aleurotrachelus socialis* and the same in the yucca plant, obtaining that *B. bassiana* has the highest levels of colonization in plants and exerts a better control on the diseases of the same (84% control).

The dual effect of *B. bassiana* has been demonstrated in both promoting growth in plants and providing protection against pests in crops (Figure 2), such as melon (*C. melo*), strawberry (*Fragaria sp*.) (Mantzoukas et al., 2022), tomato (*S. lycopersicum*) (Sui et al., 2023; Zheng et al., 2023), sugar beet (*Beta vulgaris L*) (Darsouei et al., 2024); it has been tested against the Asian corn borer *O. furnacalis*, achieving good results in biomass and protection against the borer (Sui et al., 2024b). Similarly, the resistance to abiotic stress in plants with *B. bassiana* has been tested, improving drought tolerance in tomato plants (Guo et al., 2024). It also induces resistance in potato plants against salt stress, showing higher tolerance when infected with *B. bassiana* compared to the controls (Tomilova et al., 2023).

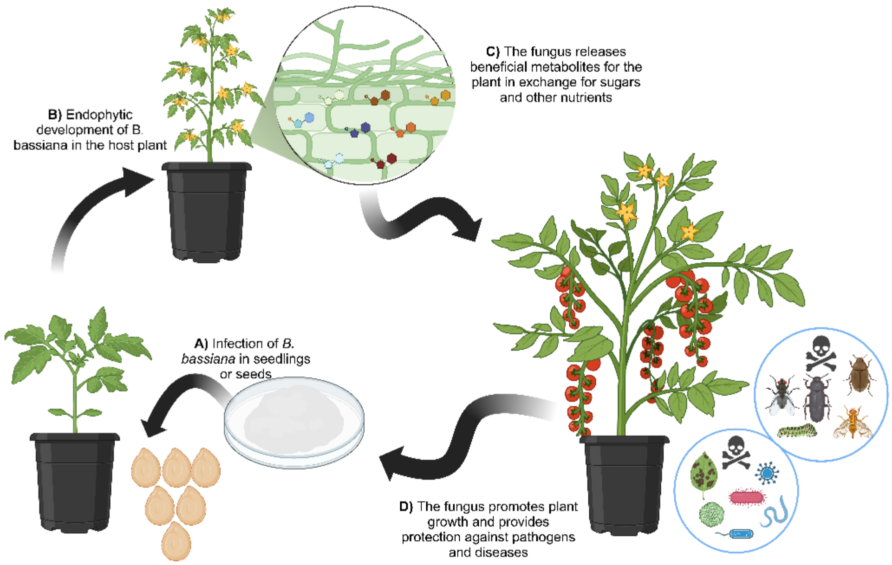

Figure 2. Dual effect of *B. bassiana* on plants (Swathy et al., 2024; Tawidian et al., 2023; Idrees et al., 2022; Zhang et al., 2022). Created in BioRender. Reyes-Silva, R. (2024) https://BioRender.com/s58x425.

Other research shows that *Beauveria spp.* has been the most studied entomopathogenic fungus as endophyte for disease control in plants demonstrating its good response in agricultural crops of tobacco (*Nicotiana tabacum*) (Taylor et al., 2014), pumpkin (*Curcubita sp.*) (Jaber & Salem, 2014), millet (*Panicum miliaceum*)(Reddy et al., 2009), tomato (*S. lycopersicum)* (Abdul et al., 2015), sweet pepper (*Capsicum annuum*) (Kumar et al., 2016), banana (*Musa paradisiaca L*) (Akello et al., 2008) coffee (*C. arabica*) (Vega et al., 2010), among others.

Promotion of host plant immunity by Beauveria

Crops are always exposed to biotic factors, which is why it was necessary to develop a defense system against threats such as bacteria, viruses, fungi, insects, herbivores, among others, which can represent potential diseases leading to death (Ngou et al., 2022a). The immune system in plants is based on Pattern Recognition Receptors (PRRs), which are extracellular, and Nucleotide Binding Leucine-Rich Receptors (NLRs), which are intracellular. The activation of these receptors triggers an immune response that in turn produces metabolites such as phytohormones and reactive oxygen species (ROS) to defend against infection or damage (Ngou et al., 2022b). In the search for the role of *B. bassiana* in improving the immune system of host plants, it was found that they directly act on the production and control of reactive oxygen species (ROS).

The symbiosis between endophytic fungi and plants leads to a significant improvement in defense against endophytic pathogens, enhancing the plant's immune system. It has been shown that the colonization of *B. bassiana* in tomato plants increases the production of reactive oxygen species (ROS) (Gupta et al., 2022). Similarly, infections by the pathogen *B. cinerea* in tomato plants also increase ROS production and, consequently, oxidative stress in the plant. Plants colonized with *B. bassiana* show higher production of SOD-type enzymes that reduce oxidative stress caused by ROS (Proietti et al., 2023).

***Beauveria* control mechanism in agricultural plant diseases**

The function of endophytic fungi in host plants is well known, as they not only protect against insects but also against pathogenic microorganisms that can cause diseases. Its effect has been tested against *B. cinerea*, inhibiting the growth of the pathogen (Sui et al., 2022), as well as against *F. oxysporum* (Nchu et al., 2022), fungi that cause significant diseases in crops such as tomatoes (*S. lycopersicum*) and grapes (*Vitis vinifera*). It has also been tested in ornamental and food crops like sunflower against the disease caused by *Sclerotinia sclerotiorum*, significantly suppressing this pest (Sui et al., 2024a). The following outlines the role of *B. bassiana* in phytopathological diseases.

(1) Direct suppression of plant pathogens

Entomopathogenic fungi such as *Beauveria* when acting as endophytes can directly suppress plant pathogens through mycoparasitism. Mycoparasitism is mainly characterized by forming hyphae wrapped around the host fungus's hyphae (Quiroz et al., 2008). The colonization of *Beauveria* occurs through plant tissues involving host recognition, spore germination, the penetration of the plant surface and the colonization of tissues (Mendiola-soto & Heil, 2014). Once *Beauveria* as endophyte colonizes the plant, it occupies a niche by depleting the nutritional resources of the plant without leaving any available for the plant pathogen. Moreover, antibiosis is produced by secondary metabolites; these confer protection against plant pathogens that cause diseases and insect pests (Ownley et al., 2010).

In vivo inoculations of *B. bassiana* in plants have been conducted to test its antiparasitic effect. Sui et al. (2023) found that in tomato plants grown in pots and in the field, once inoculated with *B. bassiana* and exposed to *B. cinerea*, the plants that showed the smallest lesions on their leaves were the experimental plants, both in pots and in the field. The effect of *B. bassiana* against the cucumber mosaic virus in cucumber plants has also been studied, observing that the virus can alter the plant's metabolites to enhance its infection. The use of the fungus mitigates the negative effect on the plant and inhibits the virus (Shaalan et al., 2022).

Some viruses, such as the beet yellowing virus, appear to not be inhibited by *B. bassiana*, but it somewhat reduces the viral load and protects against the aphid *Myzus persicae*, the main vector of the virus (Dessauvages et al., 2024). Studies have been conducted on the effect of *B. bassiana* with beneficial soil bacteria and some that are symbiotic with the fungus, showing compatibility with bacteria such as *Bacillus subtilis* (Kramski et al., 2023). However, it has also been shown to have a bactericidal effect against *Xanthomonas euvesicatoria* (Gupta et al., 2022). Positive results have also been obtained against *Pseudomonas aeruginosa, P. fluorescence, X. campestris* and *Clavibacter michiganensis* (Camele et al., 2023).

(2) Induction of systemic plant resistance.

Induced systemic resistance is an important plant defense mechanism against a wide range of plant pathogens and insect pests (Pieterse et al., 2014). This defense mechanism allows to reduce the symptoms of the disease in parts of the plant away from the site where the inducer is active. Systemic resistance induced has been demonstrated in cotton seedlings inoculated with strain 11-98 of *B. bassiana* which was soaked in the plant root and followed by folia attack of *Xanthomonas sp.,* 13 days later. Significant reduction in disease was obtained for plants not inoculated with *B. bassiana* (Ownley et al., 2010; Griffin, 2007). Suppression or delay in the development of symptoms is also considered a mechanism of SRI, this was evidenced in zucchini (*C. pepo*) plants colonized by several strains of *B. bassiana* (Jaber & Salem, 2014) where plants inoculated with the entomopathogen presented a low rate of viral multiplication compared to those that were not inoculated.

Systemic resistance in plants induced by *Beauveria spp*. has been demonstrated in multiple studies (Eltair et al., 2024; Sui *et al*., 2023; Tomilova et al., 2023; Bhattacharyya et al., 2023; Tomilova et al., 2023; Zhang et al., 2023a; Mantzoukas et al., 2022; Zhang et al., 2022), this resistance provides an advantage to the host plants, as they exhibit greater resistance to biotic (Dessauvages et al., 2024; Kramski et al., 2023; Shaalan et al., 2022) and abiotic factors (Guo et al., 2024; Tomilova et al., 2023) when infected with *B. bassiana* compared to those that are not (Sui et al., 2024a), demonstrating its potential as a beneficial endophyte in integrated pest, vector, and disease management in plants (Abd El-Wahab et al., 2023; de Oliveira et al., 2023; Yasin et al., 2022; Zamora-Áviles et al., 2022; Chouikhi et al., 2022).

(3) Promotion of plant growth

Another mechanism used by fungal entomopathogens as endophytes is the protection of their host plant through improved plant growth (Gana et al., 2022). Fungal entomopathogens have been shown to promote plant growth after endophyte establishment thus avoiding abiotic and biotic stress (Liu et al., 2022). Example of promoting plant growth is found in pumpkin (*Curcubita sp.*) plants colonized with *B. bassiana* against ZYMV (Kesh & Yadab, 2023; Jaber & Salem, 2014) which not only reduced the disease but also proved more vigorous and developed faster. The same has been demonstrated with plants exposed to *F. solani* (Deng et al., 2018) showed healthy growth and lower disease rates compared to plants not colonized.

It should also be noted that the inoculation of plants with fungal entomopathogens has induced proteins related to photosynthesis and energy metabolism, which leads to increased plant growth and disease resistance (Gómez-Vidal, 2009). The improved growth can also be attributed to the production of phytohormones as in the case of *B. bassiana* which produces siderophores under iron depletion culture conditions (Jirakkakul et al., 2014; Krasno et al., 2014). Finally, it should be noted that the ability of several species of fungal entomopathogens such as *B. bassiana*, *B. brongniartii* and *M. brunneum* depend on the method used for inoculating plants with the strains of fungi or the combination thereof.

Similarly, the promotion of plant growth produced by *B. bassiana* can explain the resistance to various types of abiotic stress, such as salinity, as it can stimulate the production of phytohormones, antioxidants, flavonoids, photosynthetic pigments, among others (Abdelhameed et al., 2024; Papantzikos et al., 2024; Akter et al., 2023). Furthermore, this fungus can be leveraged to increase yields in vegetable crops such as tomatoes (*S. lycopersicum*), onions (*Allium cepa*), potatoes (*C. tuberosum*), corn (*Z. may*), cucumbers (*C. sativus*), peppers (*Capsicum spp.*), among others (Eltair et al., 2024; Mohammed et al., 2024; Russo et al., 2023; Saragih, 2023; Zhang et al., 2023a; Gana et al., 2022; Liu et al., 2022; Shaalan et al., 2022; Zhang et al., 2022).

Current limitations and future studies

Although there are not many studies, some resistance presented by insects against *B. bassiana* has been found. Gao et al. (2022) discovered that young larvae of *Spodoptera frugiperda* produce protective and detoxifying enzymes against *B. bassiana* infections, which are characteristic of the early larval stages, potentially conferring resistance to the larvae against the fungus's infection mechanisms. Also, *S. frugiperda* produces antimicrobial peptides such as lepidopterin, which can inhibit *B. bassiana* spores (Qi et al., 2024). Some insects, like the beetle *T. castaneum*, secrete defensive compounds against pathogens, allowing them to inhibit the development of *B. bassiana* (Davyt-Colo et al., 2022).

The efficacy of metabolites extracted from *Beauveria spp*. has been tested, proving to be more stable than the fungi themselves, making it a promising tool against resistance developed by some insects to the fungus, as these insects depend on environmental conditions for development (temperature, humidity, UV light) (Kramski et al., 2023). Good results have been obtained using extracts of *Achyrocline satureioides* and *B. bassiana* against *Rhipicephalus microplus*, causing high mortality in both larvae and adults. However, when the extracts were used together with *B. bassiana*, 100% mortality was achieved (Fantatto et al., 2022). Kim et al. (2024) extracted and identified 8 metabolites (bassianin, bassianolide, beauvericin, beauveriolide I, enniatin A, A1, and B, and tenellin) present in the infection of *Tenebrio molitor* by *B. bassiana* using UPLC-Q-Orbitrap MS, with the main ones being bassianolide and beauvericin, which are promising for biopesticide development. Metabolites from *B. bassiana* have also been obtained through fermentation, including oosporein, which was able to inhibit spores of *Gibberella moniliformis* (Ávila-Hernández et al., 2022).

In the same way, it may occur that some crops are not compatible with the plant, despite the search for sustainable alternatives like inoculation with *B. bassiana*. An example is the search for pest resistance in the canola crop, *Brassica napus*, infected with *B. bassiana*, which resulted in longer germination times compared to the controls. However, it stimulated the production of flavonoids (Muola et al., 2024).

Future studies on the metabolism of *B. bassiana* that will focus on omics sciences (genomics, metabolomics, proteomics, transcriptomics, etc.) (Biswas et al., 2024; Wei et al., 2024; Hou et al., 2023; Mannino et al., 2023; Li et al., 2023a; Li et al., 2023b; Litwin et al., 2023; Sun et al., 2023; Zhang et al., 2023b; Guan et al., 2022; Li, 2022; Lin et al., 2022) will be key in understanding the genes and proteins involved in host infection, pathogen and disease protection, plant growth promotion, and the search for biotechnological metabolites of interest for the production of bioformulations that replace agrochemical products used in integrated pest management, which cause severe damage to the ecosystem and human health.

Conclusions

Entomopathogenic fungi are a unique and highly specialized group in pest insect control. Although there are more than 700 species of fungal entomopathogens (Angelone & Bidochka, 2018), most of the mushrooms sold are concentrated in the *Beauveria* species, *Metarthizium*, *Isaria* and *Lecanicillium*. In the case of *Beauveria*, the species on which the research is concentrated are *B. bassiana* and *B. brongniartii* (Vega et al., 2009) This leads to the conclusion that a better understanding of the ecology of this species would allow for the expansion of the development and uptake of dual biological control in conventional agriculture. Being *B. bassiana* a cosmopolitan species, it exhibits great genetic diversity (Li et al., 2023a; Li et al., 2022), which in turn facilitates the acquisition of strains through isolates from infected insects from various regions, with different adaptations to various pathogens and plant pests (Tian et al., 2024; Ranesi et al., 2024; Sun et al., 2023; Idrees et al., 2022).

Entomopathogens like endophytes are becoming a potential group of microbial biological control as could be observed in the collection of some studies carried out in this review. The use of *Beauveria* as a treatment for seeds introduced at an early stage of plant development allows to obtain a higher result in dual biological control, overcoming several inherent problems such as damage from UV radiation, reduced humidity and excessive precipitation (Pachoute et al., 2024; Muola et al., 2024; Akter et al., 2023; Posada & Vega, 2006).

The extent and persistence of endophytic fungal colonization within plants can be improved by repeated application of the microbial agent through foliar spraying or soaking in the soil The European Commission (Eltair et al., 2024; Mantzoukas et al., 2022; Jaber & Ownley, 2018). Finally, the challenge as researchers is to pave the way for the full potential of fungal entomopathogens as endophytes for integrated multiple pest management. However, several problems must be addressed mainly related to the consistency of plant colonization (Muola et al., 2024), subsequent endophytic protection (Guo et al., 2024; Eltair et al., 2024; Muola et al., 2024; Bhattacharyya et al., 2023), the resistance of some insects to *Beauveria spp*. (Qi et al., 2024; Davyt-Colo et al., 2022; Gao et al., 2022), the compatibility of host plants with the fungus (Muola et al., 2024), the symbiosis with endophytic and beneficial soil bacteria (Muola et al., 2024; Kramski et al., 2023; Liu et al., 2023); along with the development of new tools in the field of omics sciences, will provide a better understanding of the genes that regulate the proteins involved in the fungus metabolism, enabling the acquisition of biotechnologically relevant metabolites (Biswas et al., 2024; Litwin et al., 2023; Guan et al., 2022; Li, 2022).

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