

Macroscopic and microscopic fungi with insecticidal activity

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ABSTRACT

Agri-food production is affected by various factors, such as insect pests. Inadequate use of pesticides has generated resistance, and some pesticides have been shown to affect human health and the environment. Therefore, alternative control methods have been sought, such as the use of biocontrol with fungi; these organisms have shown activity against insect pests. Thus, this review compiles relevant and important studies that have been carried out over the last four decades. In general, fungi are divided into two large groups, macroscopic and microscopic fungi. In these two groups, possible fungal candidates with activity against insects have been found. They were subdivided into two groups: microscopic entomopathogenic fungi and macroscopic entomopathogenic fungi with basidiomata. In the case of microscopic entomopathogenic fungi, only the main species of these fungi (*Metarhizium anisopliae*, *Beauveria bassiana*, and *Isaria fumosorosea*) have been examined. These fungi present degrees of specificity at the family or closely related species level. For these three fungal species alone, more than 500 species of affected insects have been reported in this and other reviews. Finally, more than 200 species of fungi with basidiomata have been studied for their insecticidal activity. Additionally, possible compounds with insecticidal activity, such as ibotenic acid, beauvericin, ergosterol, and ostreolysin, are described. The studies found in the present review of fungi with insecticidal activity are promising. It was concluded that fungi, their compounds, and the proteins they contain may have a biotechnological application in the control of insect pests.

Key words: Entomopathogens, fungi, insect pests.

INTRODUCTION

Insect pests generate yield losses that fluctuate between 20% and 40% in crops worldwide, and their presence necessitates the use of pesticides (FAO, 2020). Traditionally, pesticides have been the most common method for controlling insect pests that affect crops; however, these chemicals also affect the environment and aquifer mantles. Beneficial organisms that have been observed to be affected by chemical residues are dung beetles (*Onthophagus taurus* Schreber, 1759) (Coleoptera: Scarabaeidae) and earthworms (*Lumbricus terrestris* Linnaeus, 1758) (Haplotaxida: Lumbricidae) (Silva et al., 2003; UNEP, 2010; Pérez-Cogollo et al., 2018). In addition, insect resistance to pesticides has developed (Naqqash et al., 2016). Therefore, the search for suitable and sustainable alternatives for the control of insect pests is gaining great interest throughout the globe. The use of fungi with insecticidal activity is one of the alternatives that has been widely investigated. In this review, we classify the possible candidates of fungi with insecticidal activity (entomopathogenic fungi), into two groups: microscopic entomopathogenic fungi and macroscopic entomopathogenic fungi, especially with basidiomata/sporocarp, structure characteristic of many species of basidiomycete fungi. These fungi have been reported for their activity against insects, and they affect several plant families, such as Fabaceae, Asclepiadaceae, Asteraceae, Myrtaceae, and Convolvulaceae (Da Costa Lima, 1956; Terán-Vargas and López-Guillén, 2014).

Studies on microscopic entomopathogenic fungi, where more than five families invade, immobilize, and kill insect pests, are available. Some microscopic entomopathogenic fungi not only control natural arthropod populations, but also establish complex relationships with plants (Hyde et al., 2019). The main characteristic of this type of fungi is the symbiotic relationship they maintain with the plant, helping to strengthen it against plant herbivorous organisms. Finally, macroscopic fungi that are basidiomycetes have been studied for their diverse medicinal and nutraceutical properties. Some basidiomycetes are reported to have insecticidal and anthelmintic activity (Barron and Thorn, 1987). However, comprehensive information on the role of fungi as insecticides is lacking. For this reason, the present review compiles relevant information on fungi and their insecticidal activity, as well as a list of their secondary metabolites and proteins reported to have possible insecticidal activity.

PEST INSECTS

Crop pests are organisms that compete with humans for the food they produce; these insects cause socioeconomic losses (Saunders et al., 1998). Some examples of the wide variety of pests (soil, staple grain, vegetable, root/tuber, fruit, and industrial crop pests) are shown in Table 1. Due to the great socioeconomic losses caused by insect pests, methods that are friendly to the environment and to human health have been sought. Therefore, fungi, which are known for their diverse medicinal and biocontrol properties, are being explored.

FUNGI

A wide diversity of fungi was reported in the first edition of the dictionary of fungi. It has been estimated that there are between 500 000 and 9 million fungal species in the world, including macroscopic and microscopic fungi. Most researchers agree that 80% of all fungi are microscopic (Hawksworth, 1991). In the case of macromycete fungi, there are an estimated 53 000 to 110 000 species (Müller and Schmit, 2007). Fungi are described as mostly filamentous organisms with apical growth and are eukaryotic, achlorophilic, and heterotrophic by absorption; they reproduce by asexual and sexual spores, and have a cell wall consisting mainly of chitin or cellulose (Herrera and Ulloa, 1990). Currently, fungi are reported to have different medicinal properties and metabolites for the control of insect pests (Barron and Thorn, 1987; De Silva et al., 2012). The use of macromycete and micromycete fungi for the control of insect pests has decreased the use and abuse of conventional insecticides (Naqqash et al., 2016). These types of fungi have been used as biological control agents due to their infection capacity against insect pests. To date, more than 750 species of entomopathogenic fungi have been described, and the isolation of new strains continues (Hyde et al., 2019).

Table 1. Variety of pests (soil, staple grain, vegetable, root/tuber, fruit, and industrial crop pests) affecting crops.

Pest type	Some affected crops	Examples of insect pests	Reference
Soil	Maize, sorghum, rice, beans, tomato, grass	<i>Phyllophaga</i> spp., <i>Gryllus</i> spp.	Bazán, 2020
Basic grains	Maize, sorghum, beans, rice, soybean	<i>Spodoptera frugiperda</i> (J.E. Smith; Lepidoptera: Noctuidae), <i>Dalbulus maidis</i> (De Long and Wolcott; Homoptera: Cicadellidae), <i>Rhyssomatus nigerrimus</i> (Fahraeus 1837; Coleoptera: Curculionidae)	Obando et al., 2006
Vegetables	Tomato, onion, peppers, cabbage, cucumber, pumpkin, melon, watermelon, etc.	<i>Bemisia</i> spp., <i>Liriomyza sativae</i> (Blanchard, 1938; Diptera: Agromyzidae), <i>Keifferia lycopersicella</i> (Walsingham, 1897; Lepidoptera: Gelechiidae)	García-Gutiérrez et al., 2001
Tubers	Yucca and potato	<i>Erinnyis ello</i> (Linnaeus, 1758) (Lepidoptera, Sphingidae), <i>Silba pendula</i> (Bezzi) (Diptera, Lonchaeidae), <i>Frankliniella williamsi</i> (Hood, 1915) (Thysanoptera, Thripidae)	Bazán, 2020
Fruit trees	Pineapple, banana, avocado, citrus fruits, mangoes	<i>Phyllophaga</i> spp., <i>Dysmicoccus brevipes</i> (Cockerell, 1893; Hemiptera, Pseudococcidae), <i>Thecla basilides</i> (Lepidoptera, Lycaenidae)	Jiménez and Rodríguez, 2014
Industrial crops	<i>Coffea arabica</i> , sugar cane, tobacco	<i>Hypothenemus hampei</i> (Ferrari, 1867; Coleoptera, Curculionidae), <i>Leucoptera coffeella</i> (Guérin-Méneville, 1842; Lepidoptera, Lyonetiidae), <i>Diatraea saccharalis</i> (Fabricius, 1794; Lepidoptera, Crambidae)	Jiménez and Rodríguez, 2014

In this work, the available information on two groups of fungi with insecticidal properties was reviewed, namely microscopic entomopathogenic fungi and macroscopic entomopathogenic fungi.

Microscopic entomopathogenic fungi

Some microscopic entomopathogenic fungi are already well studied and well known and can be found commercially. However, there are others that are still being researched. The majority of them are endophytic fungi, i.e., microorganisms that spend most or all of their life cycle colonizing host plant tissues without causing obvious damage. ‘Endophytism’ refers to a non-obstructive, asymptomatic, and transient cost-benefit association that is defined by location (not function) and that is established within the living tissues of the host plant. These fungi have shown that they can defend their host from herbivores. Some studies have reported the insecticidal activity of this type of fungi (Kusari et al., 2012; Sánchez-Fernández et al., 2013). In the section below, the reader can find some species of the orders Hypocreales (families Clavicipitaceae, Cordycipitaceae), Sebaciniales (Sebacinaceae) and Entomophthorales (Ancylistaceae, Entomophthoraceae).

Some commercial species. The most widely used species worldwide include *Metarhizium anisopliae* (Metschn.) Sorokin 1883 (Hypocreales: Clavicipitaceae) (33.9%); *Beauveria bassiana* (Bals.-Criv.) Vuill. 1912 (33.9%) (Hypocreales: Clavicipitaceae); *Isaria fumosorosea* Wize 1904 (5.8%) (formerly *Paecilomyces fumosoroseus*; Hypocreales: Cordycipitaceae), and *B. brongniartii* (Sacc.) Petch 1926 (4.1%) (De Faria and Wraight, 2007). The mechanism of action of microscopic entomopathogenic fungi follows the following process: 1) adhesion; 2) penetration of the cuticle, facilitating invasion of the haemocoel, degeneration of tissues, and high creation of the immune system of susceptible insects (here, extracellular enzymes may be involved: proteases, lipases, DNases and endoproteases, esterases, chitinases, chitobiosis and proteinases, and extracellular enzymes); 3) invasion via hyphal bodies/weakening/death of host by mechanical damage, malnutrition, and toxins, much depends here on the type of fungus and its mechanism of action; and 4) saprophytic growth involving conidiogenous cells and sporulation of the invading fungus (Khan et al., 2012; Hyde et al., 2019). Microscopic entomopathogenic fungi present different degrees of specificity at the family or closely related species level, without affecting natural enemies or natural antagonists. Table 2 shows examples of insect pests that are controlled by microscopic entomopathogenic fungi, followed by a description of these fungi used for biocontrol.

Metarhizium anisopliae has been reported on more than 300 insect pest species from more than 50 families. A related species, *M. riley* (Kepler, Rehner, and Humber 2014; Hypocreales: Clavicipitaceae), infects more than 32 insect species of the orders Coleoptera, Lepidoptera, and Orthoptera. It is most frequently found infecting Lepidoptera, such as *Spodoptera frugiperda* (J.E. Smith; Lepidoptera: Noctuidae) in maize (Monzón, 2001). Currently, several commercial brands of microbial insecticides based on *Metarhizium* spp. are available in the USA, Australia, France, Brazil, India, and other countries. The second most studied entomopathogenic fungus is *Beauveria* spp., which has been reported

Table 2. Examples of economically important pests controlled by microscopic entomopathogenic fungi.

Crop	Insect pests	Entomopathogenic fungi	Dose	Effect and time	Location	Reference
Rice	<i>Nilaparvata lugens</i> and <i>Sogatella furcifera</i> (adults)	<i>Metarhizium anisopliae</i>	1×10 ⁸ cnd mL ⁻¹	50% infection in 4 d	China	Tang et al., 2019
Maize	<i>Spodoptera frugiperda</i> (second and fourth larval stages)		1×10 ⁸ cnd mL ⁻¹	100% (second stages) and 75% mortality (fourth stages)	Cuba	Ramos et al., 2020
Macadamia	<i>Kuschelohynchus macadamiae</i>			100% mortality of adults	Australia	Khun et al., 2021
Maize cultivation	<i>Spodoptera frugiperda</i> (second and fourth larval stages)	<i>Beauveria bassiana</i>	1×10 ⁸ cnd mL ⁻¹	100% and 87% mortality (second and fourth larval stages)	Cuba	Ramos et al., 2020
Rice	<i>Sitophilus oryzae</i>	<i>Isaria fumosorosea</i>	1.81×10 ⁸ cnd mL ⁻¹	70% mortality in 14 d	Grecia	Kavallieratos et al., 2014
Mango	<i>Anastrepha ludens</i>		1×10 ⁸ cnd mL ⁻¹	84% mortality in 7 d	México	Gandarilla-Pacheco et al., 2018

Cnd: Conidia.

to attack more than 200 species of insect (Monzón, 2001). This genus is comprised of several species, including *B. bassiana*, *B. brongniartii*, *B. amorpha* (Höhn.) Minnis, S.A. Rehner & Humber 2011, and *B. velata* Samson & H.C. Evans 1982. Another entomopathogenic fungus, *I. fumosorosea*, affects more than eight species of insects. These fungi are characterized by slow action (with a predation time of 168 h) (González-Castillo et al., 2012).

Non-commercial species. The endophytic fungus *Neotyphodium coenophialum* (Morgan-Jones & W. Gams) Glenn, C.W. Bacon & Hanlin 1996 (Hypocreales: Clavicipitaceae) shows activity against heteropteran *Oncopeltus fasciatus* (Dallas, 1852; Hemiptera: Lygaeidae), and this activity may be due to alkaloids (Yates et al., 1989). Another study on endophytic fungi showed the effect of alkaloids on *Popillia japonica* (Newman, 1841; Coleoptera: Scarabaeidae) and lepidopteran *Spodoptera* spp. (Patterson et al., 1991; Riedell et al., 1991).

Furthermore, the fungus *Piriformospora indica* Sav. Verma, Aj. Varma, Rexer, G. Kost & P. Franken 1998 (Sebacinales: Sebacinaceae) has the ability to colonize the plant root and enhance plant growth (Verma et al., 1998), and has been shown, in some cases, to promote seed production and growth in *Arabidopsis* spp. (Camehl et al., 2010). *Piriformospora indica*, as a biocontrol agent, can induce the plant defense signal pathway against pathogens (Stein et al., 2008).

On the other hand, the order Entomophthorales is also found in the classification of microscopic entomopathogenic fungi. These fungi produce cell walls with chitin and, grow mainly as mycelia or hyphae; the hyphae are cenotic (without transverse walls or septa) and septa are observed in the older parts of the mycelium. The main characteristic of this group is the zygospore (formed within a zygosporangium after the fusion of specialized hyphae called gametangia within a sexual cycle). In addition, fungi belonging to the order Entomophthorales are biotrophic, meaning that can obtain nutrients from living host cells with no or no apparent harm to the hosts, in fact, the host, depends on these species of fungi (Sharma and Sharma, 2021). Several species of entomophthoral fungi have been reported, including *Conidiobolus apiculatus* (Thaxiei) (Remaudière and Keller 1980; Entomophthorales: Ancylistaceae), which attaches the cadaver to the plant by means of numerous rhizoids; *Conidiobolus coronatus* (Costantin) (Batko, 1964), a saprophytic fungus common in all soils throughout the world; and *Entomophthora planchoniana* (Cornu 1873; Entomophthorales: Entomophthoraceae), which exclusive to aphids and attacks cereal aphids. *Erynia neoaphidis* (Remaud. & Hennebert 1980; Entomophthorales) is the most common pathogen of aphids, and it also attacks pinfly. Another fungus is *Zoophthora radicans* (Brefeld Batko, 1964), a polyphagous fungus that attacks Homoptera, Diptera, and Lepidoptera (Remaudière and Latgé, 1985).

Macroscopic entomopathogenic fungi

Some fungi with basidiome are edible; they have also been reported to possess several medicinal properties, including anticancer, antimutagenic, antidiabetic, anti-inflammatory, antimicrobial, antibacterial, antifungal, antiviral, anthelmintic, and insecticidal activities (Mohammad-Fata et al., 2007; De Silva et al., 2012; Mirunalini et al., 2012; Hassan et al., 2015; Pineda-Alegría et al., 2017; Pino et al., 2019).

One of the first reports of fungal activity with basidiomata was from *Lycoperdon* (Pers.) (Agaricales: Agaricaceae). This genus was reported to anesthetize or paralyze bees by means of fungal spores (Cordier, 1876). After this report, several studies began to emerge which examined the insecticidal activity of fungi with basidiomata (Figure 1).

In the studies carried out with basidiome and their insecticidal activity (Figure 1), the number of genera and the species of fungi were observed. In total, more than 150 fungi with insecticidal activity were evaluated between 1876 and 2021. Of these, more than 90 fungi showed insecticidal activity against *Drosophila melanogaster* (Meigen, 1830; Diptera: Drosophilidae), *Spodoptera littoralis* (Boisduval, 1833), *Tribolium* spp., *Diatraea magnifactella* (Dyar 1911; Lepidoptera: Crambidae), and *Sitophilus zeamais* (Motschulsky, 1855; Coleoptera: Curculionidae); these fungi are grouped into 44 different fungal genera (Figure 2). However, it is important to consider that Mier et al. (1996) showed that fungi do not share the same insecticidal activity despite being of the same genus.

Between 1876 and 2021, the most reported fungal genera with basidiomata were *Boletus* (16%), *Tricholoma* (6%), *Hygrophoropsis* (5%), *Cortinarius* (5%), *Amanita* (4%), *Pleurotus* (4%), *Lepista* (4%), and *Clitocybe* (4%) (Figure 2). For other genera, their participation was lower, but this does not indicate that the reported insecticidal activity was nonsignificant with respect to control. One of the important characteristics of the research outlined in this review is the molecules reported to have possible insecticidal activity.

Figure 1. Examples of studies of fungi with basidiomata evaluated against insects.

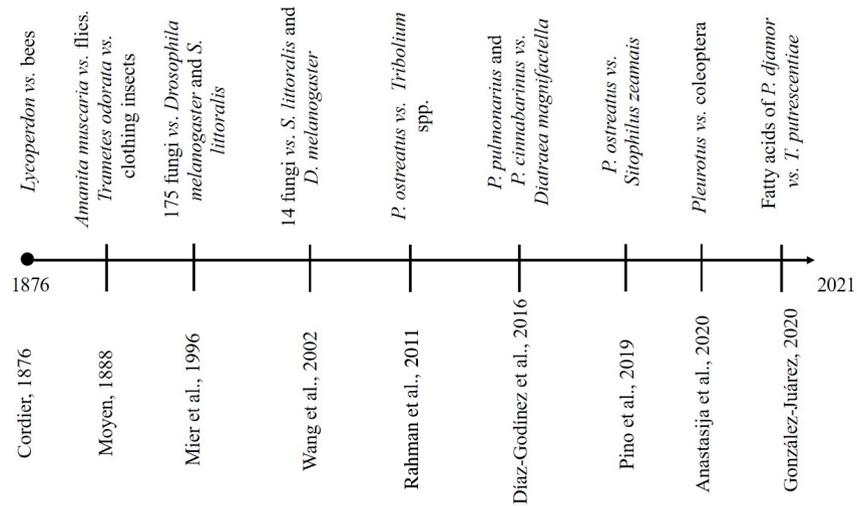
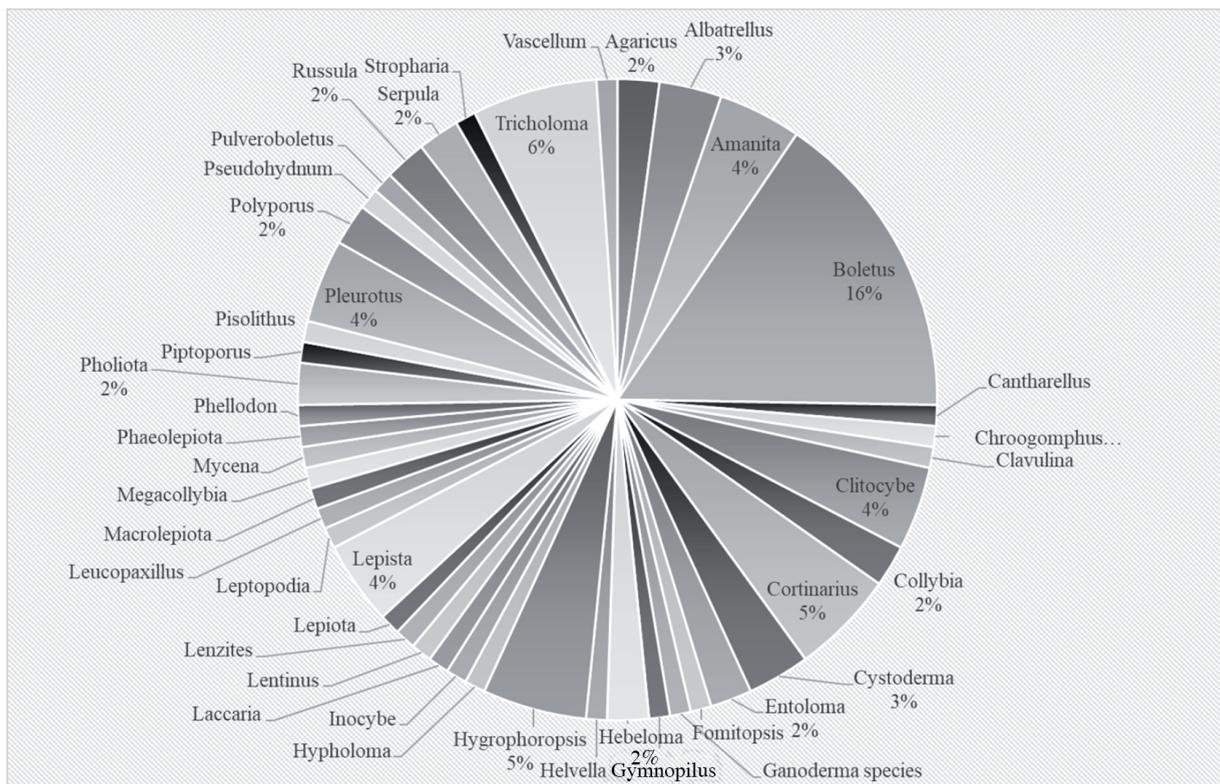


Figure 2. Percentages of prevalence (by genera) in the studies where the activity of fungi with insecticidal activity was evaluated.



INSECTICIDAL ACTIVITY OF FUNGAL SECONDARY COMPOUNDS

It is well known that secondary compounds of plants and fungi can act with a dual function, and compounds with biological activity against insects have been reported. Table 3 summarizes some secondary metabolites produced by fungi with possible insecticidal effects.

One of the compounds isolated is ibotenic acid, which can be found in *Amanita muscaria* (Lam. 1783; Agaricales: Amanitaceae) and *A. pantherina* (Krombh, 1846; Agaricales: Amanitaceae); this molecule was reported to kill flies (Wieland, 1968). Other compounds have been isolated from fungi that are possible candidates for insecticidal effects, such as amatoxins from the genus *Amanita*. Amatoxins are known to irreversibly inhibit ribonucleic acid (RNA) polymerase and are therefore toxic to all eukaryotes, except some mycophagous insects (Jaenike et al., 1983).

Additionally, the insecticidal activity of destruxins has been evaluated in many insects since 1985 (Quiot et al., 1985). Toxin bioassays have administered toxins by topical application, forced ingestion, immersion, or injection to larvae or adult insects. Destruxins cause an initial tetanic paralysis, which, in lethal doses, leads to insect death (Pedras et al., 2002). Another neurologically active compound is 2-amino-3-(1,2-dicarboxyethylthio) propanoic acid, which is an *N*-methyl-D-aspartic acid (NMDA)-sensitive glutamate receptor antagonist that can be isolated from *A. pantherina* (Fushiya et al., 1993). A study was carried out to clone the gene coding for beauvericin in *Escherichia coli* (Migula, 1895; Enterobacteriales: Enterobacteriaceae). The evaluated strains of *B. bassiana* were “wild-type”, which was confirmed with the presence of beauvericin and bassianolide, and the second strain was “bbBeasKO” in which beauvericin was inactivated and only bassianolide was active. Additionally, the third strain used was “KivrKO” where neither beauvericin nor bassianolide were present. These three strains were evaluated *in vitro* against different growth stages of *Spodoptera exigua* (Hübner, 1808; Lepidoptera: Noctuidae), *Galleria mellonella* (Linnaeus, 1756; Lepidoptera: Pyralidae) and *Helicoverpa zea* (Boddie, 1850; Lepidoptera: Noctuidae). Differences were observed in the concentration of 10^6 conidia mL⁻¹, the strain that showed the highest percentage of mortality was “wild-type”, with 98%, 80% and 60% mortality, respectively. While the second strain, “bbBeasKO”, only showed a mortality of 10% to 30%. However, in the strain where neither beauvericin nor bassianolide was expressed, the only mortality that stood out was *H. zea*, with 25% (Xu et al., 2008).

To corroborate this information, another study was conducted in 2009 (Xu et al., 2009); on this occasion, bassianolide was inactivated and the percentage of mortality was quantified. In this study, the strains used were “wild-type”, which had previously been confirmed with beauvericin and bassianolide, and “bbBsls KO #6”, which was a mutant and the expression of bassianolide was inactivated. When evaluating these two strains against *S. exigua*, *G. mellonella*, and *H. zea* insects. It was observed that, for “wild-type”, the mortality percentages were 50%, 60%, and 50% for the respective insects (10^6 conidia mL⁻¹). On the other hand, for the mutant without bassianolide, the highest mortality percentage was 20% for *H. zea* (Xu et al., 2009). These two studies reported the important role of both beauvericin and bassianolide in *B. bassiana*. In the absence of either of these compounds, it was observed that the percentage of mortality decreased in

Table 3. Secondary compounds and proteins with insecticidal activity that have been isolated from fungi.

Fungi	Possible insecticidal		Reference
	Secondary compounds	Proteins	
<i>Amanita muscaria</i> , <i>A. pantherina</i>	Ibotenic acid	-	Wieland, 1968
<i>Amanita</i>	Amatoxins	-	Jaenike et al., 1983
<i>Metarhizium anisopliae</i>	Destruxins	-	Quiot et al., 1985
<i>Neotyphodium coenophialum</i>	Alkaloids	-	Yates et al., 1989
<i>A. pantherina</i>	2-Amino-3-(1,2-dicarboxyethylthio) propanoic acid	-	Fushiya et al., 1993
<i>Amanita</i> spp., <i>Boletus</i> spp., <i>Clitocybe</i> spp., <i>Hygrophoropsis</i> spp., <i>Lepista nuda</i> , <i>Polyporus squamosus</i> , <i>Serpula lacrymans</i>	-	Haemolysin, lectin, and serpin	Wang et al., 2002
<i>Beauveria bassiana</i>	Beauvericin	-	Xu et al., 2008
<i>B. bassiana</i>	Bassianolide	-	Xu et al., 2009
<i>Pleurotus salmoneostramineus</i>	Ergosterol	-	Alexandre et al., 2017
<i>Pleurotus</i>	-	Aegerolysin, ostreolysin A6, pleurotolysin A2, and erysin	Anastasija et al., 2020

bioassays against *S. exigua*, *G. mellonella*, and *H. zea*. By 2017, the presence of ergosterol was confirmed in the fungus *P. salmoneostramineus* (Vassiljeva, 1973), and it showed anti-*Trypanosoma cruzi* (Chagas, 1909; Trypanosomatida: Trypanosomatidae) activity against trypomastigotes. The mechanism of action of ergosterol on *T. cruzi* trypomastigotes results in plasma membrane permeability, as well as depolarization of the mitochondrial membrane potential, leading to parasite death (Alexandre et al., 2017). This demonstrates that some fungi produce secondary metabolites that act as toxins against insects.

ACTIVITY OF FUNGAL PROTEINS AGAINST INSECTS

The presence of some fungal proteins with bioactivity have also been identified (Table 3). In 2002, a study conducted on the insecticidal activity of fungi (*Amanita phalloides*) (E.-J. Gilbert 1941; Agaricales: Amanitaceae), *Albatrellus cristatus* (Schaeff. Kotl. and Pouzar, 1957; Russulales: Albatrellaceae), *Boletus aereus* (Bull, 1789; Boletales: Boletaceae), *B. aemilii* (Barbier, 1915), *B. badius* (Fries, 1821), *B. subtomentosus* (Linnaeus, 1753), *Clitocybe nebularis* (Batsch, P. Kumm. 1871; Agaricales: Tricholomataceae), *C. prunulus* P. (Kumm 1871; Agaricales: Tricholomataceae), *Hygrophoropsis aurantiaca* (Marie, 1921; Boletales: Hygrophoropsidaceae), *Hygrophorus chrysodon* (Batsch Fr. 1838; Agaricales: Hygrophoraceae), *Lepista nuda* (Bull. Cooke, 1871; Agaricales: Tricholomataceae), *Polyporus squamosus* (Huds. Fr.1821; Polyporales: Polyporaceae), and *Serpula lacrymans* (Wulfen J. Schröt. 1888; Boletales: Serpulaceae) reported haemolysin, lectin, and serpin proteins. Additionally, the activity of the fungi was evaluated by means of a toxicity bioassay, and the range of the fungi evaluated was from 40% to 100% mortality (Wang et al., 2002).

In 2020, the genus *Pleurotus* was reported to produce proteins with insecticidal activity, such as aegerolysin, ostreolysin A6, pleurotolysin A2, and erysin. The mode of action of these proteins is to bind strongly to insect cells and artificial lipid membranes. Mainly, these proteins show strong selectivity towards larvae and adults of rootworm (WCR; *Diabrotica virgifera*, LeConte, 1868; Coleoptera: Chrysomelidae) and larvae of Colorado potato beetle (CPB; *Leptinotarsa decemlineata*) (Say, 1824; Coleoptera: Chrysomelidae) (Anastasija et al., 2020).

APPLICATIONS OF ENTOMOPATHOGENIC FUNGI

As fungi have been found to perform a variety of ecological functions, different application methods have been designed or are still under investigation. In addition to their insecticidal activity, these fungi can have complex relationships in the habitats where they are found, can provide N to plants, and additionally function as protectors against pathogens. These fungi have also been used commercially for biocontrol. On the one hand, edible mushrooms have been widely used for many centuries in traditional Chinese medicine due to their different anti-inflammatory, antihypertensive, antiviral, antimicrobial, cytotoxic, antitumor, anticancer, and antioxidant properties (Smiderle et al., 2008; Sánchez et al., 2015). Knowing some of the compounds present in fungi can also differentiate their applications; for example, destruxins, show diverse antimicrobial, antiviral, antiproliferative, cytotoxic, and immunosuppressive biological properties. Modified destruxins are useful in the treatment of Alzheimer's disease, as they can inhibit and prevent the generation of β -amyloid (A β) (Wang and Xu, 2012). On the other hand, the role of fungi pollutants from the environment is well known. Therefore, they have been proposed for the removal of harmful compounds (generated in the manufacture of some household products) due to their high toxicity to the environment, animals and humans. These compounds are as follows: 4-*n*-nonylphenol, triazine, dibutyltin, synthetic estrogen, hydrocarbons, heavy metals, nanoparticle biosynthesis, and the biotransformation of other compounds (Litwin et al., 2020).

CONCLUSIONS

This review showed that there are macroscopic or microscopic fungi with insecticidal activity. In addition, possible fungal compounds with insecticidal activity, such as ibotenic acid, anatoxins, destruxins, alkaloids, 2-amino-3-(1,2-dicarboxyethylthio) propanoic acid, beauvericin, bassianolide, ergosterol, and linoleic acid, are also reported. Possible proteins with insecticidal activity are also reported, including haemolysins, lectins, serpins, aegerolysin, ostreolysin A6, pleurotolysin A2, and erysin. It was concluded that fungi and their products, such as the secondary compounds and proteins they contain, may have a potential biotechnological application for the suitable and sustainable control of insect pests.

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