

BIOTRANSFORMATION AND TOXIC POLLUTANTS REMOVAL BY ENTOMOPATHOGENIC FUNGI

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Submitted May 30, 2025; Revised October 3, 2025; Accepted October 10, 2025; Published January 20, 2026

ABSTRACT

This current research has examined the impact of these hazardous agents on entomopathogenic fungi and the mechanisms that affect their survival in such conditions as the environment and agricultural fields grow contaminated with numerous anthropogenic compounds, such as pesticides. This review sheds light on entomopathogenic fungi capacity to break down harmful pollutants such as hydrocarbons, alkylphenols, organotin chemicals, synthetic estrogens, and pesticides. These fungi also create a variety of secondary metabolites that could be used as antibacterial agents or in medicine. The usage of entomopathogenic fungi has been undervalued despite their enormous potential in biocontrol procedures because of a lack of knowledge about their capabilities. In this work, we provide the information that is currently known regarding these microbes' other and unusual applications.

Keywords: Entomopathogenic fungi, Pollutant removal, Biotransformation, Biodegradation

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INTRODUCTION

Entomopathogenic fungi are bioinsecticides capable of infecting and killing arthropods. While they are primarily isolated from arthropod carcasses, their natural habitat is soil. Entomopathogenic fungi are classified into six categories: Oomycetes, Chytridiomycota, Microsporidia, Entomophthoromycota, Basidiomycota, and the most prevalent, Ascomycota. The primary ecological role of entomopathogenic fungi is the biocontrol of insect populations. Existing literature provides insights into the infectious properties of entomopathogenic

fungi, the mechanisms of infection, and their application in commercial biopesticide formulations [1].

In recent decades, rising environmental pollution has become a significant concern. Daily the substances that adversely affect ecosystem balance and living organisms are introduced into the environment. Soil-dwelling fungi are particularly sensitive to contaminants, such as herbicides, insecticides, fungicides, and heavy metals, which can lead to reduced or delayed growth, disruptions in cellular metabolic pathways,

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and damage to cellular structures. These harmful effects hinder the ability of these microorganisms to fulfill their ecological roles. However, some fungi have developed mechanisms to survive in contaminated environments [2].

Due to their high enzymatic activity, ability to produce secondary metabolites, and robust growth in culture media, entomopathogenic fungi are also being explored for various biotechnological applications, such as nanoparticle biosynthesis and the bioconversion of steroids or flavonoids, which have significant economic implications [3-5].

Entomopathogenic fungi are parasitic microorganisms capable of infecting and killing arthropods. They are primarily utilized as biopesticides in ecological farming, serving as a safe alternative to toxic chemical insecticides. Additionally, some of these fungi find applications in biotechnological processes and traditional Chinese medicine [6].

Among the known entomopathogenic fungi, the Entomophthorales (e.g., *Furia*, *Conidiobolus*, *Entomophaga*, or *Erynia*) exhibit the highest insecticidal activity. However, they are not typically used in biopreparations due to challenges in laboratory cultivation. In contrast, the most commonly used EPF are saprotrophic fungi from the Ascomycota group, which can be easily cultured. Globally, various biopesticides derived from species in the genera *Metarhizium*, *Beauveria*, *Paecilomyces*, *Isaria*, and *Lecanicillium* are available. These fungi possess a broad spectrum of activity, enabling them to infect a wide range of arthropod species [7-10].

Entomopathogenic fungi are diverse organisms that fulfill various ecological roles. For instance, species from the genera *Metarhizium* and *Beauveria*, which are often found in soil, help regulate natural arthropod populations and form complex relationships

with plants. They are known to act as endophytes in plant roots, stems, and leaves. Research has shown that *M. robertsii* and *B. bassiana* can provide nitrogen to plants during the parasitization of insects, thereby promoting plant growth [11]. *Beauveria bassiana* functions as an endophyte in about 25 plant species, aiding in the control of pests and fungal pathogens. As both a fungal endophyte and epiphyte, it colonizes leaves and shoots, enhancing plant resistance to insects and protecting against microbial pathogens by suppressing disease-causing agents or boosting plant defense responses. Similarly, *Lecanicillium* prevents fungal diseases by growing on leaf surfaces, limiting nutrient availability, producing antimicrobial compounds, and inducing plant responses while colonizing roots. In contrast, *I. fumosorosea* appears to have limited interactions with plants, likely due to its sensitivity to chemical signals secreted by plants as part of their defense mechanisms against pathogens. Interestingly, isolates of *I. fumosorosea* have been reported to infect the root nematode *Meloidogyne javanica*, although infection rates remain low. Overall, entomopathogenic fungi are primarily employed for the biocontrol of insect pests in laboratory, greenhouse, or field settings [12].

REMOVAL OF TOXIC POLLUTANTS BY ENTOMOPATHOGENIC FUNGI

In their natural habitats, entomopathogenic fungi frequently come into contact with a variety of man-made contaminants. Few research have looked at the interactions between toxic contaminants and entomopathogenic fungus, despite the fact that the processes governing the disease of insects by these microbes are generally well recognized. Endocrine-disrupting chemicals are among the most dangerous categories of anthropogenic molecules. These substances, which can be natural or synthetic, have structural similarities that allow them to bind to hormone receptors, thereby disrupting the

endocrine systems of humans and animals. This category includes compounds such as alkylphenols (e.g., nonylphenol), organotin compounds (e.g., tributyl tin), synthetic estrogens (e.g., 17 α -ethinylestradiol), and pesticides (e.g., ametryn).

Removal of 4-n-nonylphenol

Nonylphenols, which are xenoestrogens, are widely used in the production of various household products. The most prevalent form is para-nonylphenol, existing as multiple isomers that vary in the branching of their alkyl chains. These compounds are highly toxic to aquatic organisms and can accumulate in the environment, posing significant ecological risks. They primarily enter the environment as biodegradable byproducts of surfactants and detergents. 4-NPs disrupt the functioning of both human and animal endocrine systems by mimicking 17 β -estradiol and binding to estrogen receptors [13]. Additionally, these compounds negatively affect microorganisms and soil invertebrates, inhibiting plant growth.

Strains of the genus *Metarhizium* have demonstrated the ability to degrade the unbranched isomer of nonylphenol (4-n-NP). In cultures, *M. robertsii* and *M. brunneum* exhibited the highest degradation activity after 24 hours of incubation, achieving over 90% loss of the substrate. Extracts from *M. robertsii* cultures revealed 35 derivatives formed after the degradation of this xenobiotic. The proposed degradation pathway suggests that *Metarhizium* fungi possess unique capabilities to conduct multiple simultaneous mono- and dihydroxylation reactions in both the aliphatic chain and the aromatic ring of 4-n-NP [14-16]. Furthermore, these fungi can completely degrade nonylphenol in the culture environment, resulting in the formation of CO₂ and H₂O.

Removal of Triazine by entomopathogenic fungi

Triazines are herbicides characterized by a heterocyclic ring containing three unsaturated nitrogen atoms. These compounds are known to have carcinogenic effects and disrupt the endocrine system in living organisms, leading to their prohibition in the European Union; however, they still persist in the natural environment. Studies have demonstrated that *M. brunneum* can partially decompose ametryn, a type of triazine, at an initial concentration of 100 mg/L, resulting in the formation of four derivatives.

Removal of Dibutyltin by Entomopathogenic Fungi

Dibutyltin is used as a catalyst in esterification reactions and as a curing agent for silicone rubbers. It enters the environment through tributyltin breakdown products and polyvinyl chloride compounds. Immunotoxic, neurotoxic, and pro-oxidative characteristics are linked to dibutyltin. Aerated cultures of *M. robertsii* can completely biodegrade dibutyltin (initial concentration of 20 mg/L) into monobutyltin and hydroxylated MBT. The addition of vitamin C reduces oxidative stress related to tin compounds in the medium, and in the presence of this vitamin, the tested strain degrades MBT three times faster. Furthermore, the presence of natural estrogens (estrone and 17 β -estradiol) accelerates the degradation of dibutyltin, while both estrogens protect entomopathogenic fungi from oxidative stress induced by MBT in the culture medium [17-19]. The fluidity of the cell membrane in *M. robertsii* suggests its potential for degrading toxic substances. A less compact membrane structure, characterized by higher permeability, facilitates the transport of toxic compounds into the cell for degradation.

Estrogen Removal by Entomopathogenic Fungi

17 α -Ethinylestradiol is a synthetic estrogen widely present in the environment, including soil, groundwater, rivers, lakes, and seas, due to its extensive use and resistance to biodegradation. A derivative of 17 β -estradiol, it is commonly used in hormonal contraception. Various strains of *M. robertsii* can efficiently remove up to 85% of EE2 from the growth medium.

Hydrocarbons Removal

Entomopathogenic fungi are capable of assimilating n-alkanes. The metabolic pathways for the decomposition of these compounds and the enzymes involved are well understood. N-alkanes are xenobiotics frequently found in the environment and in small quantities in the insect epicuticle, which, along with the wax layer, serves as the primary barrier for EPF. Lipids with long hydrocarbon chains are present in all external layers of insects. The fungus *B. bassiana* can utilize n-alkanes (extracted from insect surfaces) as a carbon source [20]. Cytochrome P450 in the microsomal fraction first hydroxylates these molecules, which are then catabolized via β -oxidation. Additionally, synthesized straight-chain alkanes can be grown and metabolized by this fungus. These linear hydrocarbons (such as n-hexadecane or n-octacosan) can also be used by other EPF, like *M. robertsii*, as their exclusive source of carbon and energy, with cytochrome P450 aiding in the early phases of breakdown [21-24].

The ability of the entomopathogenic fungus *B. bassiana* MTCC 4580 to remove four industrial dyes from wastewater was tested. This strain demonstrated high efficiency in eliminating the dyes, achieving removal rates of up to 97% at an initial concentration of 500 mg/L. The highest removal rate was observed for Indanthrene blue at 97%, while Vat Novatic Grey and Reactive Remazol Red were removed at rates of 91% and 84%,

respectively. The mechanism behind the removal of synthetic dyes by *B. bassiana* is based on bioaccumulation rather than biodegradation.

BIOTRANSFORMATION USING ENTOMOPATHOGENIC FUNGI

Entomopathogenic fungi can perform biotransformation, leading to the generation of derivatives with higher activity. These processes are favorable, because they improve the absorbability of products.

Steroid Biotransformation

Steroids are economically significant compounds widely utilized in medicine as hormones and active drugs. Pharmaceutical-grade steroid derivatives are typically obtained through various modifications and transformations. Due to the complexity of chemical modification methods, which often involve multiple stages, microbiological transformations are frequently employed. These transformations include hydroxylation, Baeyer–Villiger oxidation, reduction, and isomerization. Among these, the hydroxylation reactions performed by filamentous fungi, are crucial for producing biologically active molecules [25].

Numerous filamentous fungi are effective in steroid transformations, including entomopathogenic fungi. Recent studies have revealed that 12 strains of *I. farinosa* can efficiently convert dehydroepiandrosterone into hydroxy derivatives. Notably, one strain, *I. farinosa*, transformed androstenediol, androstenedione, adrenosterone, 17 α -methyltestosterone, 17 β -hydroxyandrost-1,4,6-triene-3-one, and progesterone into mono- or dihydroxy derivatives with high yield and stereoselectivity [26].

Another study confirmed that *I. fumosorosea* can biotransform estrogens. Most estrogens were hydroxylated at the C-6 position and glycosylated at the C-3 position. However, the presence of a methyl group on the C-3 steroid ring completely inhibited glycosylation, indicating that a free hydroxyl

group at this position is essential for the process [27-30].

Entomopathogenic fungi also hold potential for large-scale steroid transformations, which may have industrial applications in the future. For example, *M. anisopliae*, combined with a nano-liposome technique, successfully transformed 11 α -hydroxy into 13-ethyl-gon-4-ene-3,17-dione, a key intermediate in the synthesis of the oral contraceptive desogestrel, achieving a high yield. The primary product, 11 α -hydroxy-13-ethyl-gon-4-ene-3,17-dione, was produced at a concentration of 6 g/L without compromising transformation efficiency. Additionally, the main byproduct, the 6b,11 α -dihydroxy derivative, proved advantageous for the purification of HGD.

Because *Beauveria bassiana* can manufacture useful 11 α -hydroxy intermediates of steroids in large yields, it may find use in the pharmaceutical business. But this procedure needs to be optimized. Only two hydroxylated metabolites were found in *B. bassiana* cultures treated with androst-4-ene-3,17-dione at pH 6.0. On the other hand, four hydroxylated and/or reduced metabolites were found in samples at pH 7.0. These results show that *B. bassiana* is an effective biocatalyst for the reduction of the 17-carbonyl group and 11 α -hydroxylation.

The *B. bassiana* strain ATCC7159 converts DHEA to 3b,11 α ,17b-trihydroxyandrost-5-ene when exposed to moderate concentrations of DHEA (0.83–1.0 g/L) in a mild environment (26 °C, pH 7). The addition of various compounds can enhance the biosynthesis of these pharmaceutical metabolites. For instance, incorporating n-alkane solvents as a carbon source significantly boosts the hydroxylation capacity of *B. bassiana*. Specifically, the introduction of n-dodecane (n-C12) and n-hexadecane increased the conversion of DHEA to 3b,11 α ,17b-trihydroxyandrost-5-

ene, resulting in a 22.8% mM yield of hydroxylated products in the culture medium. A distinctive aspect of *Beauveria*'s reaction mechanism is that it reduces the C-17 ketone of DHEA after the 11 α -hydroxylation, which contrasts with other microorganisms that typically activate an unfunctionalized carbon to form an 11 α -hydroxy-17-oxo derivative before producing the 3b,11 α ,17b-triol product.

Flavonoid Biotransformation

Flavonoids are derivatives of plant polyphenols, characterized as glycosides that feature O- and C-glycosidic bonds linking the base to sugar residues, typically glucose, rhamnose, galactose, xylose, and arabinose. It is believed that the sugar component of flavonoids significantly influences their absorption in the human body. Flavonoids are categorized into six classes: flavones, isoflavones, flavanones, flavanols, flavanonols, and flavan-3-ols. Due to their antioxidant, anti-inflammatory, and antibacterial properties, flavonoids offer various health benefits, including anti-tumor and immunomodulatory effects, as well as protective properties for the nervous system. Consuming foods rich in flavonoids can help prevent heart disease, diabetes, and depression. These compounds are naturally found in vegetables, fruits, cereals, wine, and tea [31-34].

Microorganisms can effectively biotransform flavonoids into flavonoid glycosides, which are better absorbed by the body. Among these microorganisms, entomopathogenic fungi (EPF) show significant potential for such processes. Currently, *Isaria* and *Beauveria* are frequently studied, while the capabilities of *Metarhizium* remain largely unexplored [35].

CONCLUSIONS

In addition to their role in biocontrol, EPF can be utilized in various ways by removing harmful substances from the environment due to their enzymes that degrade toxic

compounds of anthropogenic origin. For instance, species such as *M. robertsii* and *M. brunneum* can break down nonylphenols, triazines, tin compounds, synthetic estrogens, hydrocarbons, and industrial dyes. While interactions with heavy metals can sometimes hinder their growth or alter hyphae morphology, these fungi can also remove heavy metals from contaminated environments, including waters polluted with zinc, copper, cadmium, nickel, and chromium. They can also improve plants' capacity for phytoremediation of metals like copper, manganese, and zinc. The authors draw the conclusion from this review that EPF has significant potential for the bioproduction of silver nanoparticles with antibacterial and antifungal qualities as well as the biosynthesis of physiologically active substances used in medicine, such as hydroxylated steroids and glycosylated flavonoids.

Author(s) Contribution: Analysis and resources data, P. Sanjeev; review and proof-reading, S. Rajavarthani.

Funding: No funding involved.

Ethical Approval: Not applicable

Conflict of Interest: Nil.

Consent for Publication: All authors approved the manuscript for publication.

REFERENCES

1. Acir IH, Guenther K (2018) Endocrine-disrupting metabolites of alkylphenol ethoxylates—a critical review of analytical methods, environmental occurrences, toxicity, and regulation. *Sci Total Environ* 635:1530–1546. <https://doi.org/10.1016/j.scitotenv.2018.04.079>
2. Dou F, Wang Z, Li G, Dun B (2019) Microbial transformation of flavonoids by *Isaria fumosorosea* ACCC 37814. *Molecules* 24:1028. <https://doi.org/10.3390/molecules24061028>
3. Fan Y, Liu X, Keyhani NO et al (2017) Regulatory cascade and biological activity of *Beauveria bassiana* oosporein that limits bacterial growth after host death. *Proc Natl Acad Sci USA* 114:E1578–E1586. <https://doi.org/10.1073/pnas.1616543114>
4. Farias CP, Alves GS, Oliveira DC (2019) A consortium of fungal isolates and biochar improved the phytoremediation potential of *Jacaranda mimosifolia* D. Don and reduced copper, manganese, and zinc leaching. *J Soils Sediments*. <https://doi.org/10.1007/s11368-019-02414-3>
5. Szewczyk R, Kus'mierska A, Bernat P (2018) Ametryn removal by *Metarhizium brunneum*: biodegradation pathway proposal and metabolic background revealed. *Chemosphere* 190:174–183. <https://doi.org/10.1016/j.chemosphere.2017.10.011>
6. Taibon J, Sturm S, Seger C et al (2015) Quantitative assessment of destruxins from strawberry and maize in the lower parts per billion range: combination of a QuEChERS-based extraction protocol with a fast and selective UHPLC- QTOF-MS assay. *J Agric Food Chem* 63:5707–5713. <https://doi.org/10.1021/acs.jafc.5b01562>
7. Vega FE (2018) The use of fungal entomopathogens as endophytes in biological control: a review. *Mycologia* 110:4–30. <https://doi.org/10.1080/00275514.2017.1418578>
8. Wang C, Leger RJS (2007) The MAD1 adhesin of *Metarhizium anisopliae* links adhesion with blastospore production and virulence to insects, and the MAD2 adhesin enables attachment to plants. *Eukaryot Cell* 6:808–816. <https://doi.org/10.1128/EC.00409-06>

9. Feng P, Shang Y, Cen K, Wang C (2015) Fungal biosynthesis of the bibenzoquinone oosporein to evade insect immunity. *Proc Natl Acad Sci* 112:11365–11370. <https://doi.org/10.1073/pnas.1503200112>
10. Fiedler Z, Sosnowska D (2017) Side effects of fungicides and insecticides on entomopathogenic fungi in vitro. *J Plant Prot Res* 57:355–360. <https://doi.org/10.1515/jppr-2017-0048>
11. Gola D, Malik A, Namburath M, Ahammad SZ (2018) Removal of industrial dyes and heavy metals by *Beauveria bassiana*: FTIR, SEM, TEM and AFM investigations with Pb(II). *Environ Sci Pollut Res* 25:20486–20496. <https://doi.org/10.1007/s11356-017-0246-1>
12. Banu AN, Balasubramanian C (2014) Optimization and synthesis of silver nanoparticles using *Isaria fumosorosea* against human vector mosquitoes. *Parasitol Res* 113:3843–3851. <https://doi.org/10.1007/s00436-014-4052-0>
13. Donzelli BGG, Krasnoff SB (2016) Molecular genetics of secondary chemistry in *Metarhizium* Fungi. In: Lovett B, Leger RJS (eds) *Advances in genetics*, vol 94. Elsevier, Amsterdam, pp 365–436
14. Ali S, Huang Z, Ren S (2013) Effect of fungicides on growth, germination and cuticle-degrading enzyme production by *Lecanicillium muscarium*. *Biocontrol Sci Technol* 23:711–723. <https://doi.org/10.1080/09583157.2013.108009583157.2013>
15. Xu Y, Orozco R, Wijeratne EMK et al (2009) Biosynthesis of the cyclooligomer depsipeptide bassianolide, an insecticidal virulence factor of *Beauveria bassiana*. *Fungal Genet Biol* 46:353–364. <https://doi.org/10.1016/j.fgb.2009.03.001>
16. Ashraf S, Radhi M, Gowler P et al (2019) The polyadenylation inhibitor cordycepin reduces pain, inflammation and joint pathology in rodent models of osteoarthritis. *Sci Rep* 9:4696. <https://doi.org/10.1038/s41598-019-41140-1>
17. Kidd PS, Alvarez-Lopez V, Becerra-Castro C et al (2017) Chapter three—potential role of plant-associated bacteria in plant metal uptake and implications in phytotechnologies. *Adv Bot Res* 83:87–126
18. Lacey LA, Mercadier G (1998) The effect of selected allelochemicals on germination of conidia and blastospores and mycelial growth of the entomopathogenic fungus, *Paecilomyces fumosoroseus* (Deuteromycotina: Hyphomycetes). *Mycopathologia* 142:17–25. <https://doi.org/10.1023/A:1006963016316>
19. Asi MR, Bashir MH, Afzal M et al (2010) Compatibility of entomopathogenic fungi, *Metarhizium anisopliae* and *Paecilomyces fumosoroseus* with selective insecticides. *Pak J Bot* 42:4207–4214
20. Greenfield BPJ, Lord AM, Dudley E, Butt TM (2014) Conidia of the insect pathogenic fungus, *Metarhizium anisopliae*, fail to adhere to mosquito larval cuticle. *R Soc Open Sci* 1(2):140193. <https://doi.org/10.1098/rsos.140193>
21. Haruma T, Yamaji K, Ogawa K et al (2019) Root-endophytic *Chaetomium cupreum* chemically enhances aluminium tolerance in *Miscanthus sinensis* via increasing the aluminium detoxicants, chlorogenic acid and oosporein. *PLoS ONE* 14:e0212644. <https://doi.org/10.1371/journal.pone.0212644>

22. Jajic' I, Dudas' T, Krstovic' S et al (2019) Emerging fusarium mycotoxins fusaproliferin, beauvericin, enniatins, and moniliformin in serbian maize. *Toxins* (Basel) 11:357.
<https://doi.org/10.3390/toxins11060357>
23. Jin K, Peng G, Liu Y, Xia Y (2015) The acid trehalase, ATM1, contributes to the in vivo growth and virulence of the entomopathogenic fungus, *Metarhizium acridum*. *Fungal Genet Biol* 77:61–67.
<https://doi.org/10.1016/j.fgb.2015.03.013>
24. Mascarin GM, Jaronski ST (2016) The production and uses of *Beauveria bassiana* as a microbial insecticide. *World J Microbiol Biotechnol* 32:1–26.
<https://doi.org/10.1007/s11274-016-2131-3>
25. Supakdamrongkul P, Bhumiratana A, Chanpen W (2010) Characterization of an extracellular lipase from the bio-control fungus, *Nomuraea rileyi* MJ, and its toxicity toward *Spodoptera litura*. *J Invertebr Pathol* 105:228–235
26. Wang Q, Xu L (2012) Beauvericin, a bioactive compound produced by fungi: a short review. *Molecules* 17:2367–2377.
<https://doi.org/10.3390/molecules17032367>
27. Xiong Z, Wei Q, Chen H (2006) Microbial transformation of androst-4-ene-3,17-dione by *Beauveria bassiana*. *Steroids*. 71:979–983
<https://doi.org/10.1016/j.steroids.2006.07.007>
28. Behie SW, Bidochka MJ (2014) Ubiquity of insect-derived nitrogen transfer to plants by endophytic insect-pathogenic fungi: an additional branch of the soil nitrogen cycle. *Appl Environ Microbiol* 80:1553–1560. <https://doi.org/10.1128/AEM.03338-13>
29. Bilgo E, Lovett B, Leger RJS (2018) Native entomopathogenic *Metarhizium* spp. from Burkina Faso and their virulence against the malaria vector *Anopheles coluzzii* and non-target insects. *Parasites Vectors* 11:11–16.
<https://doi.org/10.1186/s13071-018-2796-6>
30. Yang B, Liu H, Yang J et al (2018) New insights on bioactivities and biosynthesis of flavonoid glycosides. *Trends Food Sci Technol* 79:116–124.
<https://doi.org/10.1016/j.tifs.2018.07.006>
31. Yosri M, Abdel-Aziz MM, Sayed RM (2018) Larvicidal potential of irradiated myco-insecticide from *Metarhizium anisopliae* and larvicidal synergistic effect with its mycosynthesized titanium nanoparticles (TiNPs). *J Radiat Res Appl Sci* 11:328–334.
<https://doi.org/10.1016/j.jrras.2018.06.001>
32. Keswani C, Singh HB, Hermosa R et al (2019) Antimicrobial secondary metabolites from agriculturally important fungi as next biocontrol agents. *Appl Microbiol Biotechnol* 103:9287–9303
33. Khan S, Guo L, Maimaiti Y et al (2012) Entomopathogenic fungi as microbial biocontrol agent. *Mol Plant Breed*.
<https://doi.org/10.5376/mpb.2012.03.0007>
34. Lacey LA, Grzywacz D, Shapiro-Ilan DI et al (2015) Insect pathogens as biological control agents: back to the future. *J Invertebr Pathol* 132:1–41.
<https://doi.org/10.1016/j.jip.2015.07.009>
35. Zhang YJ, Liu X, Wang M (2008) Cloning, expression and characterization of two novel cuticle-degrading serine proteases from the entomopathogenic fungus *Cordyceps sinensis*. *Res Microbiol* 159:462–469.