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REVIEW ARTICLE

Metarhizium anisopliae: Unlocking green solutions for sustainable pest management

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Abstract

Metarhizium anisopliae (Metsch.), a naturally occurring entomopathogenic fungus, has emerged as a promising green bioinsecticide with significant potential for sustainable pest management. This review explores the multifaceted capabilities of *M. anisopliae*, highlighting its mechanisms of action, efficacy against diverse agricultural pests and advantages over conventional chemical insecticides. *M. anisopliae* infects insects through direct contact, penetrating the cuticle and proliferating within the host, leading to eventual death. This biocontrol agent demonstrates high specificity, targeting a wide range of insect pests while being safe for non-target organisms, including beneficial insects, humans and the environment. Additionally, the adaptability of *M. anisopliae* to various environmental conditions and its synergistic potential when integrated with other biological control agents and sustainable agricultural practices are examined. Its potential to contribute to sustainable agriculture by reducing reliance on chemical inputs, preserving biodiversity and mitigating the adverse effects of pesticide residues underscores the importance of further research and development in this field. This review underscores the need for continued exploration and innovation to fully harness the benefits of *M. anisopliae* in modern pest management systems.

Keywords: entomopathogenic fungus; endophyte; green bioinsecticide; integrated pest management (IPM); *Metarhizium anisopliae*; toxin

Introduction

Biopesticides offer an eco-friendly sustainable alternative to chemical pesticides reducing environmental and health risks. Growing awareness and regulatory support have accelerated their global use, with the market projected to surpass USD 10 billion by 2027, growing at over 10 % annually. Entomopathogenic fungi are a key group of biopesticides that naturally infect and kill insect pests, making them highly effective in environmentally responsible pest management strategies. *Metarhizium anisopliae* (Metsch.), a prominent entomopathogenic fungus, has garnered considerable attention as a green bioinsecticide for sustainable pest management. This fungus operates through a unique mode of action, initiating infection upon direct contact with the insect cuticle, penetrating it and proliferating within the host, ultimately leading to insect mortality. Its effectiveness against a broad spectrum of pests, including agricultural nuisances such as locusts, termites and aphids, makes *M. anisopliae* a versatile tool in pest control (1). The environmental impact of *M. anisopliae* is notably favourable compared to chemical insecticides (2, 3). It poses minimal risk to non-target organisms, including beneficial insects, humans and wildlife, thus preserving ecological balance and promoting biodiversity. This biocontrol agent's compatibility with integrated pest management (IPM) strategies is another significant advantage (4). It can be used with other biological control agents and sustainable agricultural practices, enhancing the overall efficacy of pest management programs (5).

M. anisopliae produces a variety of toxins, including destruxins, which play a crucial role in its pathogenicity by disrupting insect physiological processes. These toxins contribute to the rapid decline of pest populations, further establishing *M. anisopliae* as an effective bioinsecticide (6, 7). Commercial formulations of *M. anisopliae* are available globally, with several products registered and marketed in India and other countries. These products, offered in various formulations such as spore suspensions and granules, cater to diverse agricultural needs and environmental conditions. Additionally, the endophytic capability of *M. anisopliae*, where the fungus lives within plant tissues without causing harm, provides an added layer of pest protection and enhances plant health.

M. anisopliae stands out as a promising bioinsecticide due to its targeted mode of action, environmental safety and compatibility with IPM strategies. Its potential to replace or reduce chemical insecticide usage aligns with the goals of sustainable agriculture, making it a pivotal component in modern pest management (8, 9). This study underscores the pivotal role of *M. anisopliae* as a sustainable bioinsecticide in modern pest management. By elucidating its unique mode of action, environmental benefits and integration into IPM strategies, the research highlights *M. anisopliae* is potential to mitigate the adverse effects of chemical insecticides. The exploration of its toxins, commercial applications and endophytic capabilities further emphasizes its versatility and effectiveness. This study aims to contribute to the advancement of eco-friendly pest control solutions, promoting agricultural sustainability and environmental conservation (10, 11).

Morphology and mode of action of *M. anisopliae*

M. anisopliae is a soil-dwelling entomopathogenic fungus widely used as a biocontrol agent against various insect pests. It belongs to the phylum Ascomycota and has a broad host range, making it a valuable tool in IPM programs. The fungus infects insects through direct penetration of the cuticle, causing disease and ultimately leading to the death of the host (12) (Fig. 1).

M. anisopliae produces greenish conidia (spores) that adhere to the host insect's cuticle. These conidia germinate under suitable environmental conditions, leading to the formation of a germ tube that penetrates the insect cuticle through enzymatic degradation and mechanical pressure. Once inside, the fungus proliferates in the hemocoel (body cavity), producing blastospores that disseminate throughout the host (13). During colonization, the fungus produces secondary metabolites and toxins, such as destruxins, which disrupt the host's immune system and physiological functions (14). The insect eventually succumbs to the infection due to nutrient depletion, tissue damage and the toxic effects of these metabolites (15). Finally, the fungus sporulates, emerging from the cadaver to release new conidia that can infect other hosts (16-20).

Effectiveness of *M. anisopliae* against various pests

M. anisopliae is renowned for its broad-spectrum efficacy against a variety of agricultural and forestry pests. Its versatility and eco-friendly nature make it a pivotal component of IPM strategies. Here, we explore its effectiveness against different pest groups (21, 22). The efficacy of the entomopathogenic fungus, *M. anisopliae*, was assessed through applying different conidiospore concentrations of a local isolate against third and fifth larval instars of the cotton leafworm, *Spodoptera littoralis* (Boisd.) (Lepidoptera: Noctuidae) under laboratory conditions. The lowest tested concentrations (2×10^1, 2×10^2 and 2×10^3 conidiospores/mL) caused low mortality rates on the tenth day post-treatment (2-14 % for L_3 and 0-6 % for L_5). The highest concentrations (2×10^4, 2×10^5, 2×10^6 and 2×10^7 conidiospores/mL) induced (52-90 %) mortality rate in L_3 and (50-100 %) in L_5 on the seventh day post-treatment. Death of treated larvae started on the fourth day post-treatment with the high concentrations. LC_{50} and LC_{90} values were calculated. They were higher for L_3 than for L_5 (23).

The use of *M. anisopliae* as a biological control agent against termites has been well-documented in laboratory studies. Termite mortality is dose-dependent, with higher conidia concentrations (ranging from 1×10^6 to 1×10^{10} conidia/mL) leading to greater mortality. Complete mortality is typically achieved within 3 to 21 days post-inoculation (24-27).

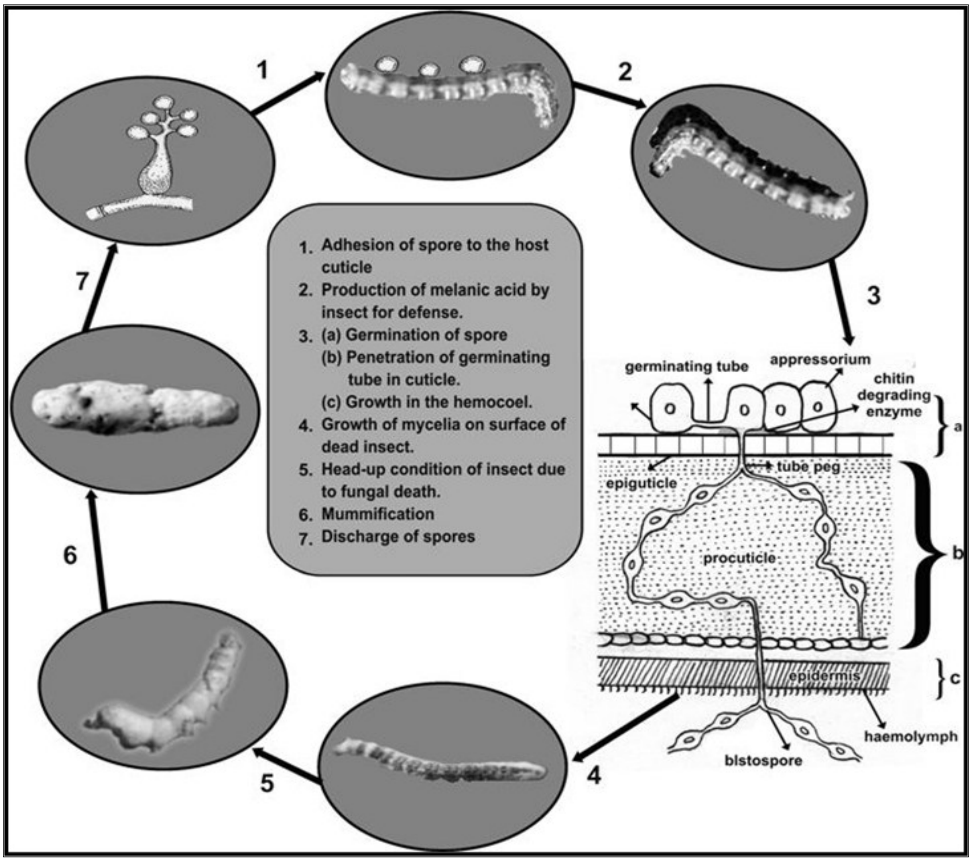

Fig. 1. Depicting the mode of action of *M. anisopliae* on insects.

The study demonstrated that *M. anisopliae* was effective against *Bactrocera cucurbitae* in both controlled and field conditions. Both contact and oral applications were found to be efficient, with higher efficacy observed through contact application (59.72 %). The pathogenicity of *M. anisopliae* increased with higher concentrations and extended time intervals. In field conditions, significantly lower fruit infestations and a marked reduction in *B. cucurbitae* populations were observed 30 days after treatment (DAT) when *M. anisopliae* was applied at a concentration of 10^8 CFU/mL (28). Although fruit flies lay their eggs under the fruit skin and the maggots develop inside, the fungal spores primarily target the adult flies, which are exposed externally during their active stages.

Lepidopteran pests, including the diamondback moth and the fall armyworm, have also been effectively managed with *M. anisopliae*, particularly in controlling the larval stages of caterpillars and moths (29). Furthermore, it has shown significant impact against hemipteran pests such as the green peach aphid and the greenhouse whitefly, leading to substantial reductions in pest populations and minimizing crop damage (30). Lastly, the fungus has been used effectively in the control of dipteran pests like *Anopheles* mosquitoes and the Mediterranean fruit fly, offering both vector control in public health and protection of fruit crops (31). A study found that *M. anisopliae* effectively controlled wheat aphid species, including *Schizaphis graminum* and *Rhopalosiphum padi*, in field conditions. The highest concentration (1×10^8 CFU/mL) achieved 85 % mortality by the 5^{th} day. This highlights *M. anisopliae* as a promising, sustainable biopesticide for managing wheat aphids in agriculture (32).

The fungal strain *M. anisopliae* CQMa421 for controlling rice planthoppers *Nilaparvata lugens* and *Sogatella furcifera*, achieving an LT_{50} of 4 days at high concentrations (1×10^8 conidia/mL) (33). Combining *M. anisopliae* with thiamethoxam reduced the LT_{50} to 1 day, significantly enhancing pest control. Field trials confirmed *M. anisopliae* CQMa421's effectiveness, particularly when used alongside thiamethoxam. *M. anisopliae* have been effectively used to control various insect pests, including *Ostrinia nubilalis* and *Callosobruchus maculatus* (Fabricius), yielding positive results (34). *M. anisopliae* has been applied to manage a diverse range of agricultural pests, including *Spodoptera litura*, *Carposina niponensis*, *Galleria mellonella*, *Prodenia litura* and several others (Table 1).

Case studies of successful integration of *M. anisopliae*

Case studies highlighting the successful integration of *M. anisopliae* demonstrate its effectiveness in sustainable pest management across various agricultural settings. For instance, in cotton farming, it has been combined with crop rotation and pheromone traps to control pests like the cotton bollworm, resulting in significant yield improvements. In coffee plantations, *M. anisopliae* has been used alongside habitat management practices to target the coffee borer beetle, enhancing overall plant health. These case studies illustrate how integrating *M. anisopliae* with complementary strategies not only reduces pest populations but also promotes environmental sustainability, benefiting both farmers and ecosystems (35).

M. anisopliae has demonstrated effective pest control across diverse agricultural settings In India, soil and foliar applications of the fungus significantly reduced cotton bollworm infestations by 60 %, enhancing yields by 15 %, while also suppressing locust swarms by 80 % (36). In China, the fungus effectively managed rice planthoppers through seed treatments and soil drenching, achieving a 70 % reduction in pest populations, while cotton fields reported a 65 % reduction in bollworm damage (37). Kenyan coffee farmers saw an 80 % decrease in coffee berry borer damage

Table 1. Efficacy of *M. anisopliae* against various pests

Pest species	Selected references
Alphitobius diaperinus (Tenebrionidae)	(63, 64)
Dysdercus peruvianus (Pyrrhocoridae)	(65)
Plutella xylostella (Plutellidae)	(66)
Trialeurodes vaporariorum (Aleyrodidae)	(67)
Encarsia formosa (Aphelinidae)	(67)
Frankliniella occidentalis (Thripidae)	(68)
Monochamus alternatus (Cerambycidae)	(68)
Peregrinus maidis (Delphacidae)	(69)
Rhyzopertha dominica (Bostrychidae)	(70, 71)
Ephestia kuehniella (Phycitidae)	(72)
Thaumatotibia leucotreta (Tortricidae)	(73, 74)
Spoladea recurvalis (Crambidae)	(75)
Tuta absoluta (Gelechiidae)	(76)
Anabrus simplex (Tettigoniidae)	(75)
Schistocerca gregaria, *Locusta migratoria* (Acrididae)	(78- 80)
Cnaphalocrocis medinalis, *Chilo partellus* *Ostrinia nubilalis* *Diatraea saccharalis* (Pyralidae)	(80, 82, 83)
Helicoverpa armigera *Spodoptera littoralis* (Noctuidae)	(23)
Trichoplusia ni (Noctuidae)	(84)
Frankliniella occidentalis (Thripidae)	(68)
Reticulitermes flavipes (Rhinotermitidae)	(85)
Diabrotica virgifera (Chrysomelidae)	(86)
Nilaparvata lugens (Delphacidae)	(87)
Hypothenemus hampei (Scolytidae)	(88)
Diatraea saccharalis	(89)

with soil applications, while Mexican tomato growers achieved an 85 % reduction in leaf miner infestations using foliar sprays. In Brazil, *M. anisopliae* applications reduced sugarcane borer infestations by 55 %, decreasing reliance on chemical pesticides (38-40).

The United States experienced a 75 % reduction in Western corn rootworm larvae. In Australia, it eradicated termite colonies by 90 % (41). Kenyan maize fields saw a 60 % decrease in stem borer infestations. In Australia, it eradicated termite colonies by 90 %. In South Africa, *M. anisopliae* decreased citrus pest incidence by 70 %. These results underscore its efficacy in diverse agricultural and pest management contexts. The treatments of *M. anisopliae* 1.15 WP @ 0.004 % stood next in order of efficacy by recording 1.20 aphid index as compared to control plot (2.07 A I) in fennel (42). *M. anisopliae* 1 % WP were found effective in reducing larval population and per cent damaged plant caused by *Spodoptera litura* in groundnut under field condition (43).

Commercial products of *M. anisopliae*

Commercial products derived from *M. anisopliae* are widely used in agricultural pest management due to their effectiveness as biocontrol agents. This entomopathogenic fungus targets a variety of pests, including beetles and caterpillars and can be formulated into different products such as granules, wettable powders and liquid suspensions (Table 2). These formulations are designed for both soil and foliar applications, offering flexibility for farmers. In India, several biopesticides are employed to manage a variety of insect pests. Met52 EC, produced by various manufacturers, targets soil dwelling and foliar insect pests (44). Bio Magic, also from various producers is effective against termites, white grubs and other soil pests (45). Green Muscle is utilized to control locusts and grasshoppers (46).

Globally, Met 52 by Novozymes is used to combat thrips, whiteflies and weevils (47). BioCeres WP, developed by BioSafe systems, targets aphids, whiteflies and thrips (48). Tick-Ex is employed in North America to control tick populations (49).

Benefits of endophytic colonization

Endophytic colonization offers numerous benefits for plants, enhancing their growth and resilience in various environments. One of the primary advantages is improved stress tolerance; endophytes can help plants withstand abiotic stresses such as drought, salinity and extreme temperatures by promoting physiological adaptations. This relationship often leads to enhanced nutrient uptake, as endophytes can assist in mobilizing nutrients from the soil, making them more accessible to the host plant. Additionally, endophytes can provide protection against pathogens by producing antifungal and antibacterial compounds, reducing the incidence of diseases and enhancing overall plant health. They also play a role in pest resistance, as some endophytes can deter herbivores or even promote the production of plant defense compounds. Furthermore, endophytic colonization can improve soil health by contributing organic matter and enhancing microbial diversity in the rhizosphere. This symbiotic relationship fosters a more robust ecosystem, leading to increased crop yields and sustainability. Overall, the presence of endophytes contributes significantly to the resilience and productivity of plants, making them a crucial component of integrated agricultural practices aimed at enhancing plant health and minimizing chemical inputs (50).

M. anisopliae, when utilized in endophytic colonization, offers a wide range of benefits for plants. One significant advantage is enhanced plant growth, as demonstrated in maize, where endophytic colonization resulted in a 15 % increase in plant height and a 20 % increase in biomass in Kenya (51). Additionally, it improves stress tolerance, as seen in wheat in the United States, where drought tolerance was enhanced, leading to 30 % higher survival rates under drought conditions (52). This fungus also promotes pest resistance, with barley crops in Germany experiencing a 40 % reduction in aphid infestation levels (53).

Moreover, *M. anisopliae* contributes to disease resistance, with studies in India showing a 50 % decrease in fusarium wilt incidence in tomatoes (54). It enhances nutrient uptake as well, increasing nitrogen and phosphorus absorption in rice by 25 % and 20 %, respectively, in China (55). Resistance to herbivores is another benefit, with maize in Brazil seeing a 45 % reduction in damage caused by the fall armyworm (56). Lastly, the fungus boosts plant immunity by activating systemic resistance, as shown in soybean crops in South Korea, which experienced a 35 % reduction in pest and pathogen attacks (57). These findings underscore the multifaceted advantages of *M. anisopliae* in promoting plant health and resilience.

Toxins from *M. anisopliae* and their roles

M. anisopliae produces several toxins and secondary metabolites that play crucial roles in its pathogenicity and effectiveness as a biocontrol agent. These toxins help in overcoming the host's immune defences, ensuring successful infection and ultimately killing the host (58). Destruxins play a role in disrupting cellular ion balance and inhibiting immune responses in insects. They cause paralysis, suppress the immune system and enhance virulence (59). Efrapeptins inhibit mitochondrial ATPase, disrupting energy metabolism, leading to cellular dysfunction and ultimately causing cell death (60). Bassianolide exhibits insecticidal properties that result in cellular damage and immune suppression (61). Pr1 and Pr2 proteases are known to degrade the insect cuticle, thereby enhancing penetration and colonization efficiency (62).

Table 2. Commercial products of *M. anisopliae*

Region	Product Name	Manufacturer	Target Pests	References
India	Met 52 EC	Various	Soil-dwelling and foliar insect pests	(82)
	Bio magic	Various	Termites, white grubs, soil pests	(83)
	Green muscle	Various	Locusts, grasshoppers	(84)
Global	Met52	Novozymes	Thrips, whiteflies, weevils	(85)
	BioCeres WP	Biosafe systems	Aphids, whiteflies, thrips	(86)
	Tick-Ex	Various	Ticks (North America)	(87)

Conclusion

M. anisopliae stands out as a sustainable and eco-friendly alternative to chemical insecticides. Its targeted action against pests, combined with minimal environmental impact and high specificity towards non-target organisms, makes it a valuable tool in IPM strategies. Future research on *M. anisopliae* should prioritize genetic improvement to develop more virulent strains with enhanced pathogenicity against target pests. This can be achieved through techniques such as selective breeding and genetic engineering, potentially leading to strains that are more resilient to environmental stressors and have a broader host range. Additionally, exploring novel formulation strategies, such as encapsulation or the use of nanoparticles, could significantly enhance the stability and efficacy of *M. anisopliae* in various agricultural settings. Combining *M. anisopliae* with other biocontrol agents or integrating it into precision agriculture systems may also improve its impact on pest management. Overall, these research avenues hold promise for maximizing the potential of *M. anisopliae* as an effective biocontrol agent in sustainable agricultural practices.

Authors' contributions

SSP collected the data and drafted the manuscript. RVR and BS revised the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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