BOTANICAL INSECTICIDE AND ENTOMOPATHOGENIC FUNGI IN TERMITE MANAGEMENT: A COMPREHENSIVE REVIEW

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Abstract. Bio-rational pesticides, specifically botanicals, as well as entomopathogenic fungi, play a crucial role in the management of insect pest populations. A substantial portion of agricultural land in our country is affected by termite infestations, resulting in significant losses within the plant kingdom, as well as to buildings and agricultural yields globally, thereby contributing to food insecurity. Application of botanicals and entomopathogenic fungi has demonstrated promising results in the effective management of termite populations. Botanicals are characterized by their natural compounds with insecticidal properties. They are capable of managing termite infestations through their toxicity, repellent effects, or disruption of physiological processes. Furthermore, botanicals are biodegradable and considered safer for non-target organisms and the environment. Entomopathogenic fungi, specifically *Metarhizium anisopliae* and *Beauveria bassiana*, represent significant fungal pathogens that effectively infect and eliminate termite populations. Their mechanism of action involves direct contact, as these fungi penetrate the cuticle of the termites and proliferate within the host organism. Subsequently, they release toxins that result in the host's mortality. These fungi exhibit species selectivity, thereby minimizing any detrimental effects on non-target insects and organisms. The application of entomopathogenic fungi offers a long-term control solution, which can reduce the necessity for repeated treatments. Incorporating these fungi into integrated pest management strategies enhances overall efficiency, sustainability, and provides an environmentally safe alternative. This review offers a comprehensive examination of plant-derived insecticides, including their active ingredients, mechanisms of action, and methods of field application. Additionally, it highlights the pivotal role that botanical solutions play in managing termite populations.
Keywords: *plant-based insecticides, termite control, biocontrol agents, Metarhizium anisopliae, Beauveria bassiana*

Introduction

Termites are subterranean insects belonging to the order Blattodea. This classification is rooted in the Greek word "blatta," which translates to cockroach, reflecting their evolutionary connection to other insects that prefer darkness (Kirton, 2005). Termites were originally classified under the order Isoptera. These insects play a vital role in their ecosystems, often referred to as social engineers. Their activities contribute significantly to environmental health by performing essential functions such as decomposing organic matter, enhancing soil fertility, and loosening soil structure (Khan et al., 2018). Additionally, termites help in the recycling of nutrients, promoting soil formation and providing food sources for both domestic and wild animals. Despite their ecological contributions, these pests are significant concerns in agriculture, forestry, and structural integrity (Govorushko, 2019). They are known to cause extensive damage to wood and

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wood products, which can impact human structures such as houses and buildings, as well as forests and other wooden resources (Ghaly and Edwards, 2011). Their presence can lead to considerable economic losses due to the destruction they cause (Meyer Rochow, 2005). Crop losses attributable to increased termite activity have been reported on a global scale. The worldwide economic impact of termite infestation is approximately 50 billion USD (Subekti et al., 2015). In India, termites represent a significant threat to various crops, particularly in regions subject to humid conditions and high soil moisture conditions that means excess water (Subekti et al., 2015). Termites and insecticides are intrinsically linked, as numerous insecticides are employed to manage termite populations effectively. Commonly utilized insecticides for termite control include fipronil, imidacloprid, and bifenthrin. These compounds function by disrupting the nervous system of termites, ultimately resulting in their mortality or the collapse of their colonies (Xiaohu et al., 2020). Chemical treatments to termites are known for their effectiveness in eradicating these pests. However, it is essential to consider the potential environmental risks associated with their use. Many pesticides can contaminate soil and water, posing a threat to local wildlife and ecosystems. For instance, when these chemicals seep into the ground, they can adversely affect beneficial insects, birds, and fish found in nearby water bodies. Understanding these impacts is crucial for making informed decisions about termite control methods. Certain chemicals exhibit resistance to decomposition, allowing them to persist in the environment for extended periods (Rattan, 2010). This persistence can result in bioaccumulation, a process whereby harmful substances accumulate in organisms over time. As these contaminated organisms are consumed by other species, the toxins can ascend the food chain, ultimately impacting larger animals and humans who ingest them. Moreover, the production and application of these pesticides contribute significantly to air pollution, exacerbating climate change and diminishing air quality (Rattan, 2010). Although chemical treatments may provide rapid solutions to termite infestations, they can generate enduring and widespread repercussions for the environment.

Various non-chemical strategies have been explored for termite management, including the distraction of termite mounds, removal of the queen, and flooding mounds with water. However, these methods have not proven to be significantly effective (Ghaly and Edwards, 2011).

Plants with insecticidal properties can be regarded as a powerful alternative to chemical pesticides. Bio-pesticides are generally extracted from various parts of plants, including their leaves, flowers, fruits, seeds, wood, and roots (Saxena et al., 2014). Some well-known examples of these botanical pesticides are azadirachtin, pyrethrin, sabadilla, nicotine, ryanodine, jatropha, etc. (Verma et al., 2009). Regarding termites and their management, using botanicals has been successful and botanicals plays a major role in termite control (Rana et al., 2021). The crude extracts of botanicals and essential oils have been tested against termite populations. Additionally, compounds derived from these extracts were found to disrupt the activity of the gut microbes inside the termites. Some substances also have the ability to interfere with the microorganisms in termites' guts, impacting both their development and survival (Duke, 2018).

Apart from botanical pesticides, another important alternative to chemical control is use of entomopathogenic fungi as a biocontrol agent (Butt and Copping, 2000). Fungal control methods are gaining more importance due to their advantages, including efficient mass production and the potential to affect a variety of insect species (Gul et al., 2014). Additionally, they offer an economical and easier mode of application of

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entomopathogenic fungi, which plays a vital role in IPM also (Rath, 2000). The disease-causing potential of fungi to the insect's immune system, along with the fungus ability to develop on its cuticle, works in a complicated manner to prevent the insect growth (Huxham et al., 1989). Termites are susceptible to fungus from genera of *Metarhizium anisopliae* and *Beauveria bassiana,* they require special application and handling techniques, and they are also known to kill termites (Milner et al., 1996).

Botanicals as bio pesticides

Around 7,000 plants with 60 plant families possess insecticidal properties (Koul, 2016). Botanicals are known to possess toxic properties that are effective against termites, which include antifeedant effects, growth regulation, and termiticidal capabilities (Verma et al., 2009). The majority of botanical pesticides function as neurotoxins, targeting various sites such as voltage-gated sodium channels, voltage-gated calcium channels, the acetylcholinesterase enzyme (AChE), nicotinic acetylcholine receptors, GABA receptors, and octopamine receptors (Souto et al., 2021).

Azadirachtin is the active compound derived from the seeds of the *Azadirachta indica*, known for its potent insecticidal properties. This terpenoid complex plays a significant role in inhibiting insect growth by affecting their hormonal systems and reproductive functions, primarily through its action as a contact poison (Asaduzzaman et al., 2016). Azadirachtin serves not only as an effective insect repellent but also as an antifeedant. Recognized as one of the key botanical insecticides, azadirachtin is noteworthy for its low toxicity to mammals and its non-toxic impact on beneficial insects (Morgan, 2009). Azadirachtin serves as a significant resource in pest management, particularly within the context of sustainable agriculture, owing to its demonstrated efficacy and favorable safety profile.

The pyrethrin daisy, or *Tanacetum cinerariifolium*, contains pyrethrin, a natural substance made up of two main compounds, Pyrethrins I and II (Jeran et al., 2021). These compounds prolong the closure of sodium channels in the nervous system. This delay can cause increased nerve activity, resulting in a loss of coordinated movement, paralysis, and, in severe cases, death (Jeran et al., 2021). Pyrethrins are mainly concentrated in the flower heads of plants compared to other plant parts. Pyrethrin is a long-standing household insecticide that remains in use today, known for its rapid action and ability to quickly immobilize insects (Casida and Quistad, 1998). When it is applied at low doses, it acts as an insect repellent. One of the main advantages of pyrethrin is that it persists in the environment for only a few weeks (Gunasekara, 2004). They are applied as sprays, dusts or emulsified substances and are frequently used with synergists like pyperonyl butoxide, which inhibits detoxification enzymes in insects, thereby enhancing insecticidal activity (Todd et al., 2003).

Nicotine is highly toxic and it is derived from *Nicotiana tabacum* (Ujvary, 1999). The alkaloids nicotine, nornicotine, and anabasine function as synaptic poisons by mimicking the neurotransmitter acetylcholine. Upon ingestion by insects, these alkaloids bind to the acetylcholine receptors at the nerve synapse, leading to uncontrolled neuronal firing. This interference disrupts normal neural impulse activity, ultimately resulting in the impairment of bodily functions governed by the nervous system (Regnault-Roger and Philogène, 2008).

Jatropha curcas is a member of the Euphorbiaceae family and offers a variety of applications, particularly in the production of biofuels and as a natural pest control agent. While the botanical extracts from this plant are typically considered safe for use, it is important to note that the seeds can be toxic due to the presence of phorbol esters. Toxic varieties of *Jatropha curcas* have been identified in regions such as Mexico, Africa and

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Asia (He et al., 2011). The extracts showcase remarkable insecticidal, nematicidal, fungicidal, and antifeedant properties, offering an inspiring, environmentally friendly alternative to synthetic pesticides and championing sustainable agricultural practices (Widiyastuti and Sutardi, 2016). In addition, the extracts of *Jatropha* have been determined to be non-toxic to humans and non-target insects (Tomar et al., 2014).

Essential oils of plant origin have insecticidal properties and are also very good repellents (Isman, 2000). They may be of low molecular-weight phenylpropanoids or terpenoids (Verma et al., 2009). These terpenoids consist of monoterpenes, which are synthesized from plastids by the methylerythritol phosphate pathway, and sesquiterpenes, which are synthesized in the cytosol by the mevalonate pathway (Aharoni et al., 2005; Regnault Roger, 2012) (*Table 1*).

Table 1. *Termiticidal Effect of Different Botanical Pesticides*

Plant name	Active compound	Plant part	Termite species	Effect	Reference
Azadirachta indica	Azadirachtin	Seed, leaf	*Coptotermes fromosanus, Coptotermes gestroi*	Inhibits growth, by affecting hormonal system and reproductive functions	(Morgan, 2009)
Tanacetum cinerariifolium	Pyrethrin	Flower	*Coptotermes formosanus, Reticulitermes flavipes, Odontotermes sp.*	Prolong the closure of sodium channels in nerves system. This delay can increase nerve activity and paralysis	(Jeran et al., 2021)
Nicotiana tabacum	Nicotine	Leaves	*Odontotermes obesus, Microtermes sp., Coptotermes formosanus*	Uncontrolled neural firing, this disrupts normal neural firing	(Regnault-Roger and Philogène, 2008)
Jtropha curcas	Phorbol	Seeds, latex	*Odontotermes obesus, Coptotermes formosanus, Reticulitermes flavipes, Microtermes sp.*	Disrupts cellular signaling, digestion and behavioral disruption	(He et al., 2011)
Taiwania cryptmerioides	Cedrol & α-cadinol	Heart wood	*Reticulitermes flavipes, Coptotermes formosanus*	Affects insect behavior	(Cheng et al., 2007)
Vetiveria zizanoides	Nootkatone	Roots	*Odontotermes obesus, Microtermes sp, Reticulitermes flavipes, Coptotermes formosanus*	Causes neural disruption and hyperexitation	(Maistrello et al., 2001)
Piper nigrum	Guineensine	Seeds	*Odontotermes obesus, Reticulitermes flavipes, Coptotermes formosanus*	Blocks neuro muscular transmission	(Meepagala et al., 2006)
Sophora flavescens	Mtrine & oxymatrine	Leaf	*Coptotermes formosanus, Reticulitermes flavipes Odontotermes sp*	Affects GABA gated chloride channel, neural disruption and feeding inhibition	(Mao and Henderson, 2007)

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Anti-termite activity of botanicals

Numerous studies have been conducted in the past decade regarding the effectiveness of botanical pesticides against termites. This increase in research is attributed to the favorable insecticidal properties and the broad spectrum of activity these substances offer.

Botanical pesticides against termites have been reported since 1973. Saeki et al. (1973) reported the efficacy of essential oil of *Chamaecyparis pisifera* against *Coptotermes formosanus*. Different bio active compounds of botanicals *viz.,* cedrol and α- cadinol of *Taiwania cryptomerioides* (Cheng et al., 2007) nootkatone, cedrol and α- cadinol of *Vetiveria zizanoides* (Maistrello et al., 2001), guinunsine of *Piper nigrum* seeds (Meepagala et al., 2006), alkaloids, matrine and oxymatrine of *Sophora flavescens* leaf (Mao and Henderson, 2007), d- limonene of citrus peel extract (Raina et al., 2007), fatty acids, alpha halogenated and torreyal of *Pinus lambertiana* (Verma et al., 2009) reported against *Coptotermes formosanus.*

The toxicity of plant parts of *Tages erecta* (Singh et al., 2003), *Lantana camara* (Verma and Verma, 2006), *Pongamia pinnata* (Verma et al., 2011) were reported against *Odontotermes obesus*. *Reticulitermes speratus* susceptibility to *Azadirachta indica* (Serit, 1992) and *Cryptomerica japonica, Pseudotsga menzieii, Quercus serrata* and *Pinus densiflora* was reported by Serit (1992) and Yatagai et al. (2002). Termiticidal properties of *Murraya koenigii* leaf against *Coptotermes gestroi* studied by Muda et al. (2018). Cardanol and methyl anacardate content of *J. curcas* seed was found to be toxic against *Microcerotermes beesoni* (Singh and Sushilkumar, 2008). Lectin content of *Myracrodruon urundeuva* was identified as resistant against *Nasutitermes corniger* (Sa et al., 2008). Bakaruddin et al. (2018) reported that tannins of *Phyllanthus niruri* was toxic against *Globitermes sulphureus* and *Coptotermes gestroi*.

Azadirachtin possesses significant repellent properties, making it challenging for termites to consume wood materials that have been treated with it. This characteristic contributes to a reduction in wood damage and enhances termite mortality rates (Zhang et al., 2021). An investigation was conducted to explore anti-termite strategies, focusing on the use of neem seed kernel extract. Different concentrations (20%, 10%, and 5%) of the extract were tested in both hot and cold water against *Coptotermes curvignathus*. The results showed that these treatments were less effective in controlling the termite population (Ahmed et al., 2016). A study investigated the effects of methanol and n-hexane extracts from neem seeds at various concentrations of 2%, 4%, and 8%. Notably, the methanol extract at an 8% concentration demonstrated a remarkable result, achieving 100% termite mortality by the third day of the experiment (Morina et al., 2023).

Murugan and Vasugi (2011) conducted a study to investigate the bioactivity of entomopathogenic nematodes and neem seed kernel extract in relation to *Reticulitermes flavipes* worker termites. The findings indicated that neem seed kernel extract (NSKE) did not adversely affect the survivability of nematodes; however, it significantly impacted the mortality of termites. At a concentration of 1.0% NSKE, there was a noted 40% mortality rate among termites by the fourth day of the experiment. When the concentration was increased to 4.0%, the mortality rate rose to 70%.

A study examined the repellence and toxicity of neem leaf extract, municipal waste extract, and carbofuran against *Macrotermes bellicosus* termites, using the filter paper impregnation method with concentrations from 0-25%. Neem leaf extract showed the highest repellence at 58.8%, followed by municipal waste at 46.9% and carbofuran at 36.7%. In terms of toxicity, carbofuran was the most toxic at 82.2% for a 20% concentration, followed by municipal waste at 57.5% and neem leaf extract at 51.8%. The

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study concluded that neem leaf extract has the highest repellence, while carbofuran has the highest toxicity (Ogbedeh et al., 2020).

A comparative study was conducted to assess the toxicity levels of pyrethrin, chlorpyrifos, bifenthrin, and imidacloprid against *Coptotermes formosanus* by filter paper method. The results showed that chlorpyrifos exhibited the highest toxicity, followed by bifenthrin, pyrethrin, and imidacloprid. It was concluded that pyrethrin demonstrated greater toxicity than imidacloprid (Xiaohu et al., 2020).

A study was conducted to evaluate the efficacy of nicotine extract as an anti-termite agent, utilizing various concentrations of 20%, 10%, and 5%. These concentrations were prepared using both cold and hot water methods. The findings revealed that a 20% concentration of nicotine extract in cold water resulted in a 100% mortality rate among termites. Conversely, a decline in mortality rates was observed with the 10% and 5% concentrations. The observed effects indicate that nicotine exhibits poisoning characteristics akin to those of organophosphate and carbamate insecticides (Ahmed et al., 2016).

A study examined the effectiveness of botanical extracts from *Azadirachta indica*, *Nicotiana tabacum*, and *Jatropha curcas* as termiticides against *Macrotermes subhyalinus* through laboratory and field experiments. The combination of *Azadirachta indica* and *Nicotiana tabacum* achieved 100% termite mortality within 4 h, while other combinations reached similar results after 6 h. In open-field tests, the mixture of *Azadirachta indica*, *Nicotiana tabacum*, and *Jatropha curcas* provided the best protection in sunlight but was less effective in shade. The study highlighted the potential of these botanical mixtures, especially *Azadirachta indica* and *Nicotiana tabacum*, for termite control (Oladipo-nee Ajayi et al., 2020).

Mortality and the tunneling behavior of *Odontotermes obesus* termites was examined, using leaf and seed extract of *Jatropha curcas*. They had maintained different concentration as 1%, 5%, 10% and one control, the control contains only the solvent while each of the concentrations were mixed with soil. Then they had concluded that mortality was less when comparing to the tunneling. They indicating the deterrence of the termite activity (Nisar et al., 2012).

The barrier and repellence properties of *Jatropha curcas* oil were evaluated against *Coptotermes vastator* and *Coptotermes formosanus* in controlled laboratory conditions. The findings indicate that the oil exhibits significant anti-feeding behavior, reduced tunneling activity, and a high mortality rate among the tested termites. Furthermore, *Jatropha curcas* oil, when combined with sand, demonstrated notable toxicity and repellency upon exposure to the termites (Acda, 2009).

The insecticidal effect of *Jatropha curcas* seed oil was tested on termites and cockroaches using a mechanical press for oil extraction, followed by n-hexane and methanol to isolate phorbol esters. Results showed that the highest efficacy occurred at 80% v/v for termites and 84% v/v for cockroaches, with mortality decreasing at lower concentrations. Treated groups exhibited significantly higher mortality compared to controls (Lateef et al., 2014).

Adams et al. (1988) reported that the leaf extract of *Juniperus sp viz.*, hexane and methanol has shown termiticidal activities. A neem pesticide formulation called Margosan-O, which included 14% neem oil and 0.3% azadirachtin was harmful to formosan subterranean termites *Coptotermes formosanus* (Grace and Yates, 1992). The study conducted by Sharma et al. (2011) showed that six plant species *viz., Acorus calamus*, *Lantana camara*, *Parthenium hausteneum*, *Pongamia glabra*, *Jatropha curcas*,

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and *Tagetes erecta*, possess potential toxicity against *Odontotermes obesus*. They also found that the rhizomes of *Acorus calamus* and aerial parts of *Tagetes erecta* are the most toxic. Additionally, Turbush (*Flourensia cernua*) leaf fractions in hexanes, diethy ether, and ethanol exhibited significant antitermite properties. The ethanol fraction contained mainly sesquiterpenoids, while the hexane fraction was rich in Monoterpenoids.

Quinines isolated from the chloroform extract of *Diospyros sylvatica* roots were toxic to *Odontotermes obesus*. Ganapaty et al. (2004) found that plumbagin, isodiospyrin and microphyllone as the primary termiticidal compounds present.

Researchers investigated the antifeedant properties of *Xylopia aethiopica* seed extracts, including aqueous methanol extract and fruit hexane extract, against the workers of *Reticulitermes speratus*. The crude extract exhibited notable antifeedant action at 1% concentration. Additional isolation of the hexane extract, six ent- kaurane diterpenes were found. (-) – kaur – 16-en-19 oic acid was found to have the strongest antifeedant activity (Lajide et al., 1995).

Essential oils of plant origin as termiticides

Zhu et al. (2001) stated that vetiver oil is the most effective against *Coptotermes formosanus* in comparison to other essential oils*, such as* cedar wood, clove bud, *Eucalyptus citriodora*, cassia leaf, vetiver grass and *Eucalyptus globulus*. Vetiver oil, nootkatone, and sesquiterpenes ketone act as a good protective shield against *Coptotermes formosanus* (Maistrello et al., 2001; Zhu et al., 2001). They act as feeding deterrents, arrestants and repellents. The feeding deterrent nootkatone results in the complete loss of *Pseudotrichonympha grassii,* a flagellate species present in the gut of formosan subterranean termite, which aid in the digestion of cellulose (Maistrello et al., 2001). Nix et al.) conducted a study and found that root mulch treatment using vetiver grass reduced wood consumption and tunnelling activity of *Coptotermes formosanus*.

Essential oils derived from plants are the mixtures of organic compounds that provide natural defence against herbivores (De Lima et al., 2013). Also, these plant-based essential oils could be a highly effective option for controlling insect pests, including termites. The active components in these oils are highly volatile due to their low molecular weights and have a brief presence in the environment (Isman and Machial, 2006). As a result, these oil-based products are regarded as environmentally friendly and a sustainable alterative to harmful pesticides used in pest control (De Lima et al., 2010). Plant oils like peppermint and clove are commonly used to repel pest such as termites, cockroaches and ants (Isman et al., 2011). Pandey et al. (2012) reported that essential oils from lemongrass (*Cymbopogon citratus*), eucalyptus (*Eucalyptus globulus*), clove (*Syzygium aromaticum*), oregano (*Origanum vulgare*), rosemary (*Rosmarinus officinalis*), cinnamon (*Cinnamomum verum*), and thyme (*Thymus vulgaris*) exhibited strong termiticidal properties when tested against *Odontotermes assamensis*. Ferruginol, manool, and nezukol were identified as antifeedants against *Coptotermes formosanus* by Scheffrahn et al. (1988) and were extracted from the wood of bald cypress (*Taxodium distichum* L). Marigold (*T. erecta*) and sweet orange (*Citrus sinensis*) oils were effective in repelling *Odontotermes obeses*, with marigold oil showing the highest repellent activity, followed by sweet orange oil (Verma et al., 2016). The toxicity of geranyl linalool, a commercially available compound, was also studied by Nagnan and Clement (1990) in relation to termites. Raina et al. (2007) used citrus peel and orange oil extract for the management of *Coptotermes formosanus* and reported that d-limonene was responsible for termite mortality.

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Botanical pesticides as wood protectant

Various trees like *Dipterocarp spp*., exhibit an immunological reaction against pests. The mortality rate of the termites had increased with the resistivity property of *Dipterocarp* woods (Mishra et al., 2020). *Shorea robusta* has exhibited high resistant against termites. It was identified that the objects which made using the sal wood exhibits resistance against the termites (Nix et al., 2006).

A study was done on evaluation of resistance, physical and mechanical properties examined using a particle board made from the waste of tobacco stalk and Paraserianthes falcataria wood particles. Both laboratory and field experiments were done, laboratory test exhibited good resistance against Coptotermes gestroi with 25% of tobacco stalks, meanwhile field test exhibited protection against Coptotermes vastator with 50% tobacco stalk content. This resistance was due to the nicotine content in the material. The addition of Paraserianthes falcataria has only improved the internal bond, stiffness, and strength (Acda and Cabangon, 2013).

The effectiveness and toxic properties of *Jatropha curcas* oil were tested against *Microcerotermes beesoni* termites at various concentrations of 1%, 5%, 10%, and 20%. The results indicated that the highest concentration (20%) provided the maximum protection for wood. Additionally, the study measured wood damage by assessing the weight loss, which ranged from 10.48% to 35.19% (Singh and Sushilkumar, 2008).

Tobacco stalks are a viable alternative for producing particleboard. As a contact poison, it functions as a rapid nerve toxin. It targets nicotinic cholinergic receptors at nerve synapses, resulting in uncontrolled nerve firing (Shivanandappa and Rajashekar, 2014). Additionally, it mimics acetylcholine (ACh) at nerve-muscle junctions in the central nervous system, ultimately resulting in toxicity for both insects and humans (Rattan, 2010).

Researchers found that the certain types of wood contain natural elements that actively defend termite infestation. By isolating these active components and testing them against termites, they have identified efficacy against termite. Sugar pine sap wood extracts from the *Pinus lambertiana* Douglas, tree and similar compounds were analyzed for their ability to deter feeding by western drywood termites, *Incisitermes minor* (Hagen). Scheffrahn and Rust (1983) had conducted a study and found that while 2-bromooctadecanoic acid exhibited deterrent activity similar to standard wood treatments, 2-iodooctadecanoic acid actually reduced termite feeding.

Yatagai et al. (2002) found that three types of wood vinegar displayed significant termiticidal effects against *Reticulitermes speratus*. These wood vinegars, labelled as Wood Vinegar A- derived from the mixture of *Cryptomeria japonica* and *Pseudostuga menziesii* wood chips, Wood Vinegar B – from *Quercus serrata* and Wood Vinegar C – from *Pinus densiflora*, were tested. The primary component of wood vinegar, acetic acid were found to possess strong termiticidal properties.

Botanicals pesticides against termite gut microbes

Termites have the unique ability to digest cellulose, allowing them to feed on a variety of cellulosic materials. The symbiotic microbes found in the hindgut of termites play a crucial role in breaking down the cellulose that the termites consume (Brune and Ohkuma, 2011). Higher termites belong to the Termitidae family, which includes many widely occurring species; also, their gut consists of bacteria. While flagellated protozoa inhabit the guts of lower termites, they are absent in higher termites. Lower termites are a

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primitive group of termites compared to the higher termites. The survival of termites is closely tied to their gut symbionts, which can cause starvation if they are not present. The gut microflora in termites is diverse and varies between species, influenced by various environmental factors (Santhoshkumar et al., 2024).

Doolittle et al. (2007) studied the potential of three natural products like capsaicin, gledistschia and neem extract to reduce the bacterial load in the hind gut of formosan subterranean termites. The populations of *Pseudotrichonympha grassii* and spirochaetes were reduced, and 100% of the termites were killed by the highest neem extract dosage of 1 ppm. Qureshi (2012) reported that a significant increase in termite mortality and the death of gut flagellates was analyzed due to the activity of extracts from the leaves of *Mentha arviensis* on *Coptotermes heimi* and *Hypotermes indicola*. Rana et al. (2021) proved that the leaf extracts of *Dalbergia sissoo*, *Heterophragma adenophylum*, *Grewia asiatica* and *Punica granatum* reduced the gut protozoans of termites.

Advantages and disadvantages

Botanical insecticides offer benefits like rapid environmental degradation, low risk, and minimal toxicity to beneficial species (Shivkumara et al., 2019). They break down easily and do not persist in the environment. Neem-based formulations are the most common, followed by pyrethrins and eucalyptus oil. These pesticides play a vital role in integrated pest management by minimizing bioaccumulation and being selective toward non-target species (Grdisa and Grsic, 2013). However, challenges in commercialization include quality control and product standardization, as well as potential pest resistance.

While generally low in toxicity to mammals, some botanical pesticides, like pyrethrin and rotenone, can harm aquatic life. Nicotine is toxic to both insects and warm-blooded animals, and phytotoxicity can affect crops like tomatoes and brinjals. Although plant-based pesticides are generally safe for humans, some species, such as Aconitum spp. and Ricinus communis, are highly toxic. Neem contains multiple bioactive compounds, with azadirachtin being photosensitive and rapidly degrading in sunlight. Developing pyrethrin-based products for the organic market is complicated by the need for synergists to enhance stability and effectiveness.

Role of entomopathogenic fungi in termite management

The entomopathogenic fungi are more environmentally friendly than chemical pesticides and have low toxicity to mammals (Balachander et al., 2009). Certain fungi facilitate the translocation of nitrogen, thereby benefiting associated plants such as beans, wheat, soybeans, and switchgrass in exchange for carbon. These fungi do not enter the body of insects via oral ingestion; rather, they penetrate directly through the exoskeleton. They serve as essential components in various biocontrol strategies (Behie, 2015).

An entomopathogenic fungus is an alternative biocontrol agent to chemical control of termites, as an alternative to chemical control of termites and it plays a major role in integrated pest management (Carruthers et al., 1991). The use of entomopathogenic fungi for termite management has been reported as successful. Around 750 species of fungi have been found as entomopathogenic fungi, but only a small number of entomopathogenic fungal agents are being used widely against insects. Many fungal genera such as *Termitaria, Neotermus, Metirolella, Laboulbenia, Antennopsis, Metarhizium, Beauveria, Leboulbeniopsis* and *Coreomyceptosis* have found to parasitize termites (Milner et al., 1996). The toxicity of fungi against insects mainly depends on

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their ability to germinate and penetrate the insect cuticle, as well as the insect's immune response to resist fungal growth (Huxham et al., 1989). Recently, the fungal management against termite is getting more importance as it has many advantages such as easier mass production techniques and inexpensive mode of application.

Metarhizium anisopliae is an entomopathogenic agent which exhibits green color conidial cells that causes green muscadine disease to the host. Thrips, white grubs, ticks and some species of termites like *Odontotermes* sp., *Reticulitermes* sp. and *Co. formosanus* were the host range of *Metarhizium anisopliae* (Bahiense et al., 2006) Effective myco-insecticides for the management of termites were strains of *Metarhizium anisopliae* C4-B is a fungal isolate found as *Metarhizium anisopliae* lead to sudden mortality of formosan subterranean termites (Sapkota, 2018). Balachander et al. (2009) had isolated Ma2 and Ma13 of *Metarhizium anisopliae* and identified as it shows pathogenicity against the workers of *Odontotermes sp* in laboratory conditions.

Milner et al. (2003) made a study on five entomopathogenic fungi like Beauveria bassiana, Metarhizium flavoviride, Metarhizium anisopliae, Paecilomyces lilacinus and Purpureocillium fumosoroseum against Odontotermes obesus and found that the termites were easily susceptible to infection. It was discovered that the over exposure to the infections Aspergillus sp. and Isaria dumodorosea Wright and Lax (2013) worker termites are found more susceptible than others. Two fungi demonstrated a high mortality rate among workers in termite colonies. The method for transferring fungal mycelium to termite colonies during the pre-sporophytic phase involves injecting the fungus into the colonies, allowing the spores to develop. However, this technique is effective only if the termites transport the mycelium to their fungal colony and deposit it instead of consuming it. The entomopathogenic fungus Beauveria bassiana has been shown to be highly toxic to a wide range of insect species in both temperate and tropical regions.

Entomopathogenic fungi are having many advantages in the pest management. They are safer for the non-target insects, humans, wildlife etc. Also they give minimum risk for the pollinators, predator insects and beneficial insects (Butt et al., 2001). They minimize the effect on the beneficial insects or the non-target organisms by the species selectivity of these entomopathogenic fungi and this specificity helps in maintaining the ecological balance (Shah and Pell, 2003). Generally, the insects can develop resistance against the chemical insecticides but they cannot build the resistance against entomopathogenic fungi. This is mainly due to the mode of action of the fungal complex on the insects like penetrating in to the cuticle of the insect body and generate within the host (Lacey et al., 1997). They can establish and can continue their life cycle within the host body. So their ability to exist in the environment will reduces the need of reapplication of the fungi. Also provides a long-term pest control (Chandler et al., 1997). So this technique can be used as the integrated pest management by combining biological, cultural and mechanical methods effectively to enhance pest management. This can be the best sustainable and comprehensive control strategy (Zimmermann, 2007). So the dependence on chemical pesticides can be decreased, thus mitigating the negative impacts of chemical pesticides (Meyling and Eilenberg, 2007). The formulations of entomopathogenic fungi are dusts, sprays or granules and making it suitable for various applications. This enhances their practical use in agricultural world.

The termites ingest the spores and eliminate them with their feces. The spores mixed with the fecal matter are viable, but they cannot germinate due to the antifungal properties of termites (Rosengaus et al., 1998). Fungal spores that attach to termites can cause infection. Infected termites may wander freely but can gain some immunity through

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interactions with healthy workers. They are also somewhat protected by fecal matter, which reduces disease spread.

Termites are very much sensitive for light, temperature and humid conditions. They have poor vision but their sense of smell is very much developed. The termites can easily identify the conidial spores from strains of the *Metarhizium anisopliae* and activate a warning alarm and assemble around each individual with the dust of the spore. Rosengaus et al. (1998) and Traniello et al. (2002) studied the behavioral defense mechanism and identified that, in large colonies, social grooming behavior between the termites makes the treatment with spores unproductive. Also, they identified that through this social grooming behavior they remove all the spores from the treated termites (*Fig. 1; Table 2*).

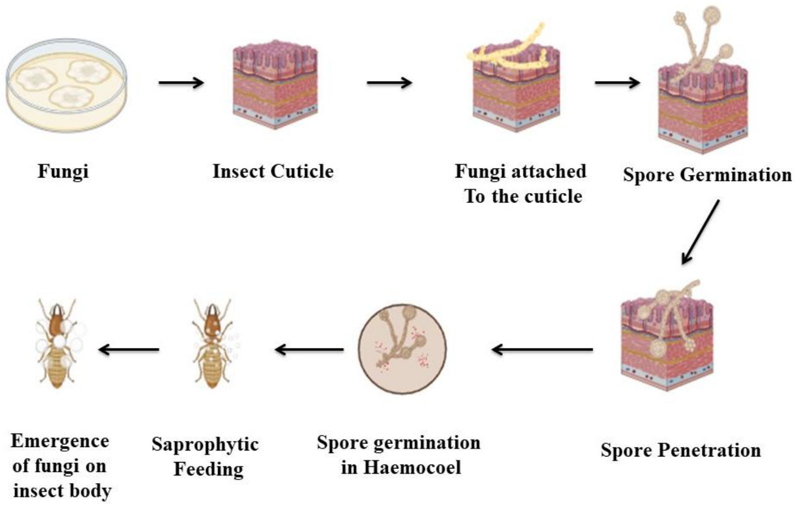

Figure 1. *Illustration of how the entomopathogenic fungi grow when they come into contact with the termite*

Table 2. *Efficacy of Metarhizium anisopliae and Beauveria bassiana against different species of termites*

Termite species	References
Coptotermes formosanus	(Wright et al., 2002; Krutmuang and Mekchay, 2005; Hussain et al., 2010)
Coptotermes curvignathus	(Yii et al., 2016)
Odontoterms spp	(Balachander et al., 2013; Ambele et al., 2020)
Microcerotermes diversus	(Cheraghi et al., 2013)
Macrotermes obesi	(Singha et al., 2011)
Microtermes beesoni	(Roy et al., 2020)
Reticulitermes speratus	(Shimizu and Yamaji, 2003)
Macrotermes sp	(Sileshi et al., 2013)
Heterotermes sp.	(Paiva Guimaraes et al., 2019)
Anacanthotermes vagans	(Fallahzadeh et al., 2019)

Grooming behavior of termites

Entomopathogenic fungi have emerged as a promising alternative for termite control; however, their implementation has encountered several challenges. One significant obstacle is the uncertainty regarding how termite hygiene behaviors influence infections

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caused by pathogenic fungi. Grooming, a well-documented social hygiene behavior among termites that promotes colony health, remains not fully understood in terms of its role and mechanisms for eliminating microbes (Yanagawa et al., 2012). Gaining insights into how insects perceive pathogens that stimulate grooming behavior is essential, as this information could enhance the effective use of such pathogens in termite management. Overall, while termites individually exhibit susceptibility to a variety of fungi, different isolates from the same species can show a considerable range of virulence (Cole, 2019).

Researchers investigated the grooming behavior of termites and the role of antennae by studying groups with and without antennae inoculated with fungal conidia. Antennae were removed from anesthetized termites, and both groups were reared in a dark chamber for a week to allow healing. Afterward, all termites were inoculated with *Metarhizium anisopliae* (Cole, 2019). To observe grooming behavior, five termites were placed in a low-light Petri dish, and the frequency of mouthpart touching among nestmates was measured through photographs, comparing results between the two groups. The findings indicated that termites without antennae touched their nestmates more often than those with antennae. Additionally, the group of termites without antennae exhibited more grooming behavior in the Petri dish. (Yanagawa et al., 2010). Coming to the role of antennae in grooming behavior, Dhanarajan (1980) and Myles (2002) proposed that the contact between the antennae plays an important role in triggering the grooming behavior among termites. They concluded that Termites starts grooming behavior when they touch each other with their antennae. Yanagawa et al. (2009) conducted an experiment for testing the grooming behavior in antennae. They collected the termites and removed both the antennae and observed the behavior of the termites. Surprisingly, even without antenna they started grooming each other. They concluded that antenna may not be essential for the grooming behavior. So the exact role of antenna in grooming behavior is still ambiguous.

Novel method for application of botanical pesticides and entomopathogenic fungi

One of the recent methods for termite control is baiting, which uses materials like cardboard or timber as bait containing cellulose. Physical barriers, such as pie plates and strip shielding, are employed to keep the bait separate from termites (Kalotermitidae, 2013). Bait stations provide a long-term solution, acting slowly to reduce the colony without immediate destruction of termites. They can use either toxic or nontoxic baits, with worker termites spreading the bait throughout the colony. Regular maintenance of bait stations is crucial for effective infestation clearing. Advance is a preferred bait for termites. Successful baiting requires proper installation, monitoring, replenishment, and thorough surveillance of the structure. Termite baits can effectively eliminate a colony if maintained properly, leading to a termite-free environment through regular inspections. The delayed action of these baits is crucial; if they act too quickly, dead termites may cause the colony to relocate. It is essential for all colony members to have time to feed on affected workers.

The bait combines cellulose or wood to attract termites and is treated with substances like nematodes that carry toxins or fungal spores that parasitize them. Bait stations are placed underground around buildings. Worker termites consume the bait and share it with the colony through trophallaxis, leading to a gradual decrease in the population and eventual eradication. The design and size of the bait are crucial, as larger baits attract termites more effectively (Evans and Gleeson, 2006) (*Table 3*).

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Table 3. *Application forms, advantages and disadvantages of the botanicals and entomopathogenic fungi*

Application form	Benefits	Bottlenecks	Reference
Below ground bait station: Installed in soil around structure	Environmentally friendly, minimal use of pesticide, targets entire colony through trophallaxis	Delayed effectiveness may take months also, Requires regular maintenance and monitoring	(Kalotermitidae, 2013).
Above ground bait: Placed directly on the termite infested areas	Direct application to active infestation, reduces the use of chemical pesticides	Only useful in structures in structures without soil	(Kalotermitidae, 2013).
Physical barriers: Pie plates, strip shielding	Protects bait from other organisms, enhance bait longevity	Additional installation effort is needed	(Evans and Gleeson, 2006)
Biological additives: Nematodes and fungal spores: incorporated in to bait to introduce pathogens to termite colony	Eco-friendly, reduces chemical use, targets termites specifically	Variable effectiveness depending on environmental conditions, May require specific application knowledge	(Evans and Gleeson, 2006)

Conclusion

Termites pose a significant threat to the plant kingdom and wooden structures, leading to considerable economic challenges in both tropical and subtropical regions. While synthetic termiticides are commonly used and effectively control termite populations, concerns remain about their harmful effects on the environment and non-target insect species. This has created an urgent need for environmentally safer alternatives. Non-chemical methods, such as plant-based insecticides derived from botanicals and entomopathogenic fungi, provide more sustainable solutions with numerous benefits. These include biodegradability, local availability, minimal impact on non-target species, and the prevention of resistance development. The active compounds responsible for termite management can be isolated, characterized, formulated, and field-tested to assess their potential as commercial termiticides. This review explores current termite control options available today, highlighting the potential of these bio-pesticides for effective termite management.

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