

Challenges And Opportunities In Termite Control: An Indian Perspectives

Radhika Sharma¹, Neha Rana¹, Reshma Sinha^{2*}, Asha Poonia³, Ramneek Kaur⁴

1.Department of Biology and Environmental Sciences, College of Basic Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishwavidyalaya, Palampur, Himachal Pradesh, India

2.Department of Animal Sciences, School of Life Sciences, Central University of Himachal Pradesh, India

3.Department of Zoology, CBLU, Bhiwani, India

4.Department of Zoology, Dev Samaj College, Ferozepur City, Punjab, India

ABSTRACT

Termites are serious pests of tropical and subtropical region, costing billions of dollars in damage to wood and related structures. Termite infestations pose significant challenges in India, impacting both urban and rural settings. As the country continues to experience rapid urbanization and infrastructural development, effective termite control measures have become increasingly essential. In India, where termites thrive due to favourable climatic conditions and diverse construction practices, the impact of termite infestations is particularly severe. Adequate knowledge about the destructive species of India is of vital importance for working out the best suitable termite control strategies. This review produces current research findings regarding termite control methods in India, evaluates their effectiveness, and identifies critical challenges and knowledge gaps in the existing literature.

Keywords: Biological control; Integrated termite management; Subterranean termites; Termiticides

INTRODUCTION

Termites are eusocial insects belonging to the order Blattodea. Recent research depicted termites to belong to lineage of cockroaches and not a separate insect order (Isoptera) as previously thought (Inward et al., 2007; Evangelista et al., 2019; Liu et al., 2025). There are approximately 1000 known species of termites in Africa, 435 species in Asian countries, over 400 species in South Africa, over 360 species in Australia, around 50 species in North America, and only 10 species reported in Europe (Kumar et al., 2020).

Termites serve an important part in recycling, providing food for other animals and improving soil fertility, but also have negative consequences, such as damage to wooden structures, forestry, and agriculture (UNEP, 2000). Millions of rupees are spent every year to maintain poles, bridges, dams, underground cables, buildings, and pipes that have been damaged by termites (UNEP, 2000). Due to their small size and camouflage in wood their presence can

be difficult to detect, and they usually cause significant harm before being noticed.

METHODOLOGY

This research includes data gathering, compilation, and assembly from a variety of sources, including the Indian Council of Agricultural Research (ICAR's) digital library and databases, the Agricultural University Palampur's online library portal, library references, symposia/seminars/conferences/workshops, and internet browsing from Google Scholar, PubMed, and Scopus using keywords such as 'termite', 'termite control', and 'termite damage'. A thorough search strategy was implemented to identify relevant literature, prioritizing studies with strong methodologies. The selection process focused on peer-reviewed research papers, specifically those addressing termite control strategies. Studies lacking sufficient experimental data or failing to directly explore termite management were excluded. This analysis provides a focused review of research on the evolution of various termite control techniques, with

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

particular attention to the significance of termites as a major pest in India.

ECONOMIC LOSSES CAUSED BY TERMITE

Termites inflict over 280 million rupees in damage in India each year. (Mahapatro and Chatterjee, 2018; Poonia et al. 2019). Economically significant families of termites are Kalotermitidae, Hodotermitidae, Termitidae and Rhinotermitidae. So far out of 337 known sp. from India, only 35 are known to be harmful (Mahapatro and Kumar, 2013). Major subterranean destructive genera in India are - *Odontotermes* sp., *Coptotermes* sp., *Heterotermes* sp., *Microcerotermes* sp., *Microtermes* sp., and *Trinervitermes* sp. (Rajagopal, 2002; Rouland-Lefèvre, 2011).

Termites devour cellulose, but can also damage plastic, leather, and practically any other soft substance (Verkerk, 1990) (Fig. 1). Termites can indirectly damage structures they do not consume through behaviors that alter moisture levels and soil stability. Subterranean termites, for instance, construct mud tubes to maintain the humidity they require for survival, leading to increased moisture accumulation in building materials. This can cause wood to decay and attract other pests, further compromising structural integrity (Ghaly & Edwards 2011). Even when termites don't directly consume non cellulosic materials their tunneling can weaken connections and result in soil displacement beneath

foundations, causing uneven settling and potential structural issues. (Chouvenc et al., 2011). Thus, termites cause significant economic losses in India, affecting various sectors such as agriculture, forestry, and infrastructure. In the agricultural sector, termites target crops and plantation trees, leading to yield reductions and decreased productivity (Patil et al., 2017). Termites can wreak havoc on crops from the moment they are planted to the moment they are harvested. Termites are estimated to have caused damage to roughly 25% of maize crops, resulting in a loss of around 1,478 million rupees in a year (Verma et al., 2018). A study conducted in Maharashtra (India) estimated that termite damage caused a 10-30% loss in sugarcane production in a year (Ganapathy et al., 2019). Furthermore, as compared to irrigated crops, rain-fed crops are damaged at a rate of 20-25% higher. Similarly, in forestry, termites damage timber, leading to substantial economic losses (Acharya et al., 2019).

In the urban and rural infrastructure sectors, termites pose a significant threat to buildings, wooden structures, and utility poles (Bhagat et al., 2019). The cost of repairing termite-infested structures can be substantial, with studies estimating billions of dollars in annual losses globally (Ghaly and Edwards, 2011). It is estimated that due to termites there is a loss of more than 20 billion dollars per year globally (Govorushko, 2019).

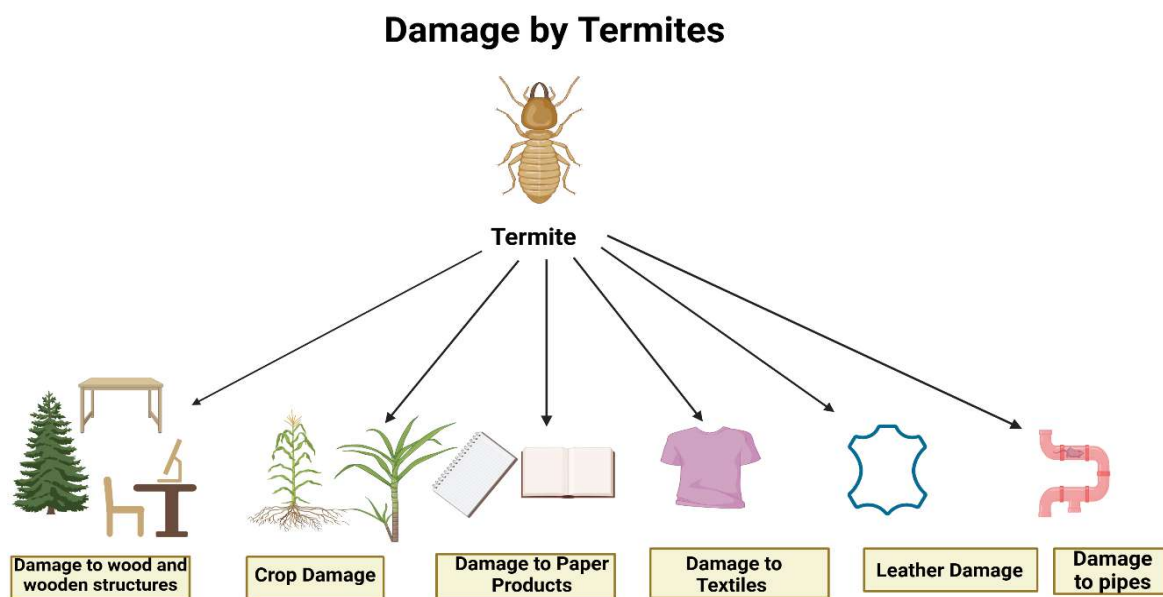


Fig. 1. Products affected by termite infestation.

TERMITE CONTROL

The pest control market is experiencing rapid growth, with the industry projected to expand by USD 10.75 billion at a compound annual growth rate (CAGR) of 7.38% between 2023 and 2028 (Technavio, 2024). In both the residential and commercial sectors, people are using pest control services on a regular basis. It becomes pertinent to discuss the presently available termite control strategies. Present control measures for termites are discussed below-

1. Chemical control: Termiticides

The effectiveness of termite control products, including termiticides, depends on their mode of action (Silver and Soderlund 2005). There are two categories of termiticides: repellents and non-repellents (Table 1). Repellent termiticides work by creating a chemical barrier that repels termites, preventing them from entering treated areas. These chemicals, such as pyrethroids (e.g., Permethrin, Cypermethrin), deter termites from accessing structures and can be used as preventive treatments. On the other hand, non-repellent termiticides, such as

Fipronil, Thiamethoxam and Imidacloprid, are designed to be undetectable by termites (Acda, 2014; Rust and Su, 2012). Instead, when termites come into contact with non-repellent termiticides, they unknowingly transfer the chemical to other colony members, including the queen, leading to the gradual elimination of the entire colony (Parman and Vargo, 2010 & Potter and Hillery, 2002). Non-repellent termiticides provide a more targeted and long-lasting solution, as they exploit the social behaviour and grooming habits of termites (Neoh et al. 2012). Some of these non-repellents disrupt the proton channels hence obstructing the insect's ability to produce energy (Silver and Soderlund, 2005) and others interrupt the functioning of voltage-gated sodium channels of the nervous system of insects while Chlorantraniliprole (anthranilicdiamide) targets the ryanamide receptors and cause paralysis, impaired muscles regulation, and eventual death of the insect (Fig. 2). The current pre-construction anti-termite treatment involves the use of pneumatic spray nozzles to render a water-based termiticide at the site before it gets covered with concrete slabs.

Table 1. List of termite repellents and non-repellents

Repellents	Non-Repellents
Carbamate (Organochlorine)	Creosote
Organophosphate	Dichloro Diphenyl Trichloroethane (DDT)*, Ethylene Dibromide*
Pyrethroid	Sodium Arsenate
Bifenthrin	Pentachlorophenol*
Cypermethrin*	Trichlorobenzene
Cyfluthrin	Fipronil
Cyhalothrin	Chlorfenapyr
Deltamethrin	Indoxacarb
Fenvalerate	Imidacloprid
Flucythrinate	Chlorantraniliprole
Lambda-Tefluthrin	Thiamethoxam
Permethrin	Abamectin
Tralomethrine	Hexaflumuron
Phenothrin	Diflubenzuron
Allethrin	Hydramethylnon
Tetramethrin	Borates (Such As Boric Acid And Sodium Borate)

* currently banned in India

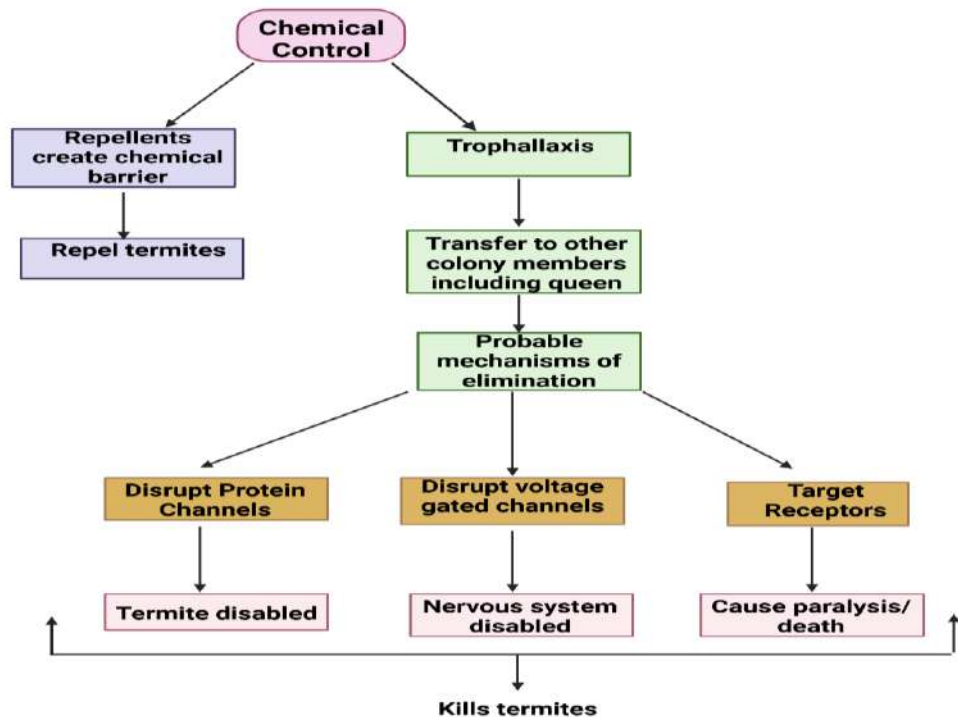


Fig. 2. Mechanism of Chemical control of termites.

1.1. Baiting

Monitoring and baiting approach has been followed as a kind of chemical control since late 20th century for the management of subterranean termites (Lax and Osbrink, 2003). This method involves strategically placing bait stations or traps in areas where termite activity is detected. The bait stations contain cellulose-based materials that are highly attractive to termites. These materials are combined with a slow-acting toxic substance that termites feed on and then carry back to their colony, effectively distributing the poison throughout the colony (Su 2019). The toxic substance may be an insect growth regulator, chitin synthesis inhibitor, or a slow-acting toxicant. Baiting method is more beneficial in controlling the lower termites (Rhinotermitidae) as compared to the higher termites (Ngee et al. 2004). A number of toxic compounds such as hydramethylnon, avermectin B1, sulfluramid and A-9248 are metabolic inhibitor and reported to exhibit slow acting and non-repellant activity against termites (Su, 2019). Proper maintenance and monitoring of bait stations is one of the important conditions to achieve desired results. The disadvantage with this baiting system is that it is costly at initial levels, involving lot of labour for regular maintenance and monitoring.

1.2. Chitin Synthesis Inhibitor

CSI are one of the most popular baiting system. In contrast to other metabolic inhibitors, CSIs exhibit a unique characteristic of dose-independent lethal time, coupled with their non-repellent and slow-action properties, rendering them highly effective in the eradication of termite colonies (Su, 2019). Various CSIs, including diflubenzuron, chlorflurazuron, triflumuron, noviflumuron, and novaluron, have been utilized and assessed for their efficacy in termite control through baiting methods (Verma et al., 2009; Chouvenec and Su, 2017; Shults et al., 2021).

In a laboratory investigation conducted by Su (2015), a fluid bait formulation was evaluated, consisting of cellulose and finely ground phagostimulants combined with 0.5% hexaflumuron and 1% methylcellulose solution. This bait was tested against both *Coptotermes formosanus* and *Reticulitermes virginicus*, resulting in an observed mortality rate of approximately 90% for both termite species within an eight-week timeframe. A separate study on Chitin Synthesis Inhibitor (CSI) baits corroborated that, in a field setting, only a fraction of a subterranean termite colony actively forages on a CSI bait at any given time. This observation implies that only a relatively small proportion of worker termites may need to

consume a CSI bait for the effective elimination of an entire colony, as highlighted by Gordon et al. (2022).

In India, the Exterra Termite Interception and Baiting System has been evaluated for its effectiveness in managing termite infestations in buildings. This system utilizes alpha-cellulose powder containing chlorfluazuron to eliminate colonies of various subterranean termite species (Broadbent 2011). Another research focused on developing and evaluating effective baits against *Anacanthotermes turkestanicus*, causing significant damage in Central Asia. While the study's primary focus was Central Asia, the findings may offer insights applicable to similar termite species in India. (Togaev et al. 2024).

Chemical control for termites can pose environmental and health risks due to toxic substances and require careful application. Additionally, termites may develop resistance to these chemicals, and the treatment may not effectively penetrate all areas of a colony, potentially leaving parts of the infestation untreated.

2. Physical Methods

Some common examples of physical control are physical barrier systems, pie plates, and strip

shielding. Physical treatment may also employ heating, freezing, electricity, and microwaves in some situations. Physical barriers (Fig. 3) are categorized into toxic and nontoxic. The nontoxic physical barriers consist of sand or gravel aggregates, metal mesh, sheeting etc. Being hard structures, they exclude entry of termites (Lenz et al. 2000), and comprises of graded particles like sand, crushed rock, glass, granites, basalt etc., solid sheet material (high-grade stainless steel, certain plastics, marine-grade aluminum) and woven stainless-steel mesh (high-grade stainless steel) (UNEP, 2000).

Toxic physical barriers are a termite control approach that combines the use of physical barriers with toxic materials to create a double-layered defence against termites. One common example is the incorporation of toxicants like borates or sodium borate into physical barriers. These toxicants are impregnated into the building materials or applied as coatings on surfaces such as wood or concrete during construction. Termites that attempt to breach the physical barrier encounter the toxic material, which disrupts their digestive systems and hampers their ability to feed and survive (Ghani, 2021).

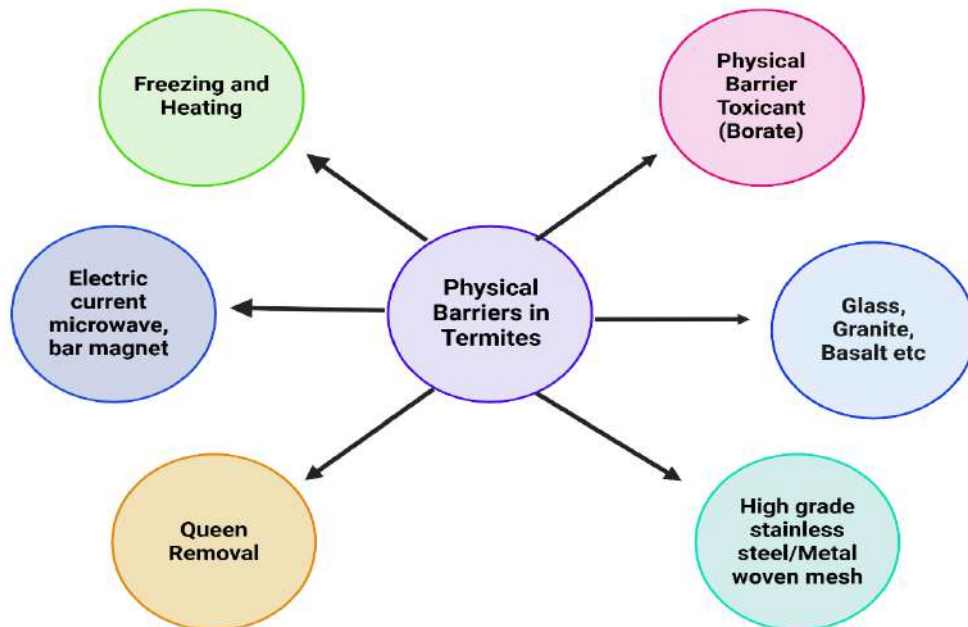


Fig. 3. Physical barriers in termite control

For total building treatment against dry wood termites, heat treatment is also an alternative against chemical fumigation. In heat treatment, termites are either exposed to intense heat of over 45°C for about an hour or by reducing the temperatures to sub-zero. The tiny crystals of ice so formed eventually kill them. A treatment with the electric current involves giving electric shock of 9000 V to 960000 V to the infested wood. An Electro-Gun is placed on one side of the infested timber, with supply of electrical shock at low current intensity (0.5 amp), high voltage (90,000 V), and high frequency (60,000 cycles). Placing strong bar magnets in the soil next to a new termite mound is also one of the ways to control termite growth as magnetism stop mound growth (Kumari et al., 2013).

Among non-destructive methods of termite control, radiations use is quite effective being odourless, noiseless, does not cause any harm to the environment and is comparatively easy to apply. It was observed that 45 to 60 minutes exposure of electromagnetic waves causes termites to lose stability and they lie down. Nakai et al. (2009) applied two different ranges (high, 5.8 GHz and low, 2.45 GHz) microwave energy frequencies to the subterranean termites *Coptotermes formosanus* and drywood termites *Incisitermes minor*. Results reported that the mortality rate of termites was more at the high microwave energy exposed for the longest irradiation time 2hr. Another method includes the destruction of the mounds of the termites to remove the queen and the king. This approach is labour-intensive as it involves manual destroying

mounds since the mounds' building materials are difficult to work with and have large dimensions. The achievement rate of this methods lacks 100% efficacy as the queen, may be hidden deep inside (Akutse et al. 2012).

A detailed compilation of Indian Traditional Knowledge (ITK) practices documents various non-chemical methods for termite management. These techniques include the use of physical barriers, mechanical nest destruction, placing cow dung cakes inside termitaria, lighting fires, removing termite queens manually, applying ash to the soil, painting tree trunks with mineral oil, and utilizing termite-resistant timbers such as Mahua for construction beams. These practices are comprehensively described by Mahapatro et al. (2017).

Physical methods of termite control, such as barriers or heat treatments, are often not very effective because they only address the termites in immediate contact and may not reach all colonies or nest sites. Termites can also quickly bypass or re-infest areas that were treated, making these methods less reliable for long-term control.

3. Biological Control

Biological control of termites refers to use of biological entity such as predators, parasitoids, pathogens, entomo-pathogenic fungi, nematodes, and bacteria in order to curb and manage insect population (Fig. 4).

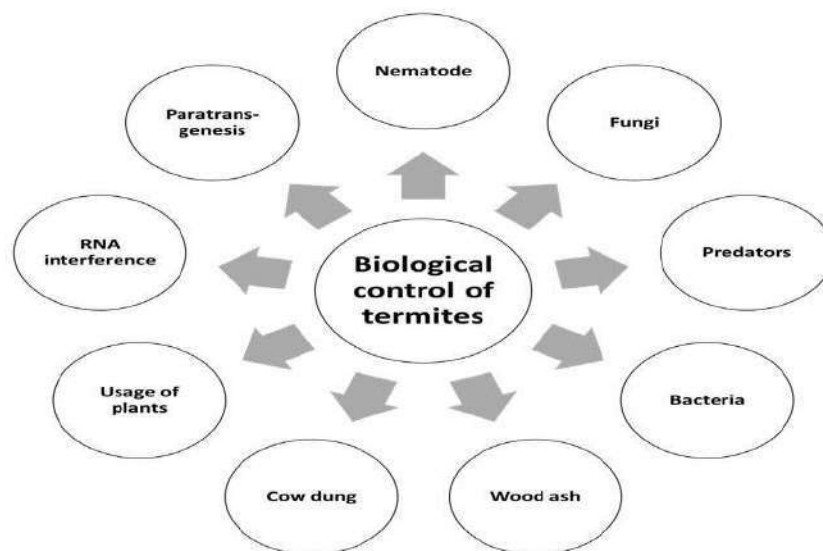


Fig. 4. Biological control of termites

3.1. Fungi

Entomopathogenic fungi have shown to play a significant role in natural termite control (Table 2.) (Chouvenec et al., 2011). The fungi have properties similar to the slow-acting chemicals (Grace et al. 1992). Milner et al. (1998) reviewed the broad

diversity of fungal pathogens which can harm termites. Laboratory experiments have been done for use of entomopathogenic fungus, *Metarhizium anisopliae* treated baits for the management of *Microcerotermes diversus*, and these baits were found to be effective (Cheraghi et al., 2013).

Table 2. Fungal species pathogenic to termites

S. No.	Fungal Species	Target termite species	References
1.	<i>Aspergillus sp.</i>	<i>Microcerotermes beelsoni</i>	Pandey et al. (2013)
2.	<i>Aspergillus flavus</i>	<i>Coptotermes formosanus</i>	Henderson (2007)
3.	<i>Aspergillus fumigatus</i>	<i>Coptotermes formosanus</i>	Chai (1995)
4.	<i>Beauveria bassiana</i>	<i>Cornitermes cumulans</i>	Neves and Alves (1999)
5.	<i>Conidiobolus sp.</i>	<i>Coptotermes curvignathus</i>	Altson (1947)
6.	<i>Conidiobolus coronatus</i>	<i>Coptotermes curvignathus</i>	Sajap et al. (1997)
7.	<i>Entomophthora coronate</i>	<i>Reticulitermes flavipes</i>	Yendol and Paschke (1965)
8.	<i>Gliocladium virens</i>	<i>Reticulitermes sp.</i>	Kramm and West (1982)
9.	<i>Gloeophyllum trabeum</i>	<i>Coptotermes formosanus</i>	Grace et al. (1992)
10.	<i>Isaria fumosorosea</i>	<i>Coptotermes formosanus</i>	Wright and Lax (2013)
11.	<i>Metarhizium anisopliae</i>	<i>Cornitermes cumulans</i>	Neves and Alves (1999)
12.	<i>Metarhizium anisopliae</i>	<i>Odontotermes obesus</i>	Khan et al. (1993)
13.	<i>Metarhizium flavovirides</i>	<i>Coptotermes formosanus</i>	Wells et al. (1995)
14.	<i>Metarhizium flavoviride</i> var. <i>Minus</i>	<i>Odontotermes obesus</i>	Khan et al. (1993)
15.	<i>Paecilomyces lilacinus</i>	<i>Odontotermes obesus</i>	Khan et al. (1993)
16.	<i>Paecilomyces cicadae</i>	<i>Coptotermes formosanus</i>	Chai (1995)

Several studies have highlighted the potential of entomopathogenic fungi for controlling termite species in India. *Metarhizium anisopliae* has shown effectiveness against *Odontotermes obesus*, one of the most destructive termite species in India, with laboratory experiments demonstrating its ability to reduce termite populations significantly (Khan et al., 1993). Similarly, *Beauveria bassiana* has been proven effective against *Coptotermes heimi* and *Coptotermes gestroi*, both of which are widespread in India and cause severe damage to buildings and crops (Neves & Alves, 1999). *Paecilomyces lilacinus*, another promising species, has also been effective against *Odontotermes obesus* (Khan et al., 1993). Additionally, *Aspergillus* species, such as *Aspergillus*

flavus and *Aspergillus fumigatus*, have shown potential for controlling *Coptotermes formosanus*, and it is likely they could affect similar Indian species like *Coptotermes heimi* (Chai, 1995; Henderson, 2007).

3.2. Nematodes

Certain species of nematodes, specifically entomopathogenic nematodes, have been found to be effective in controlling termite populations (Honigberg 1970; Yamin 1980; Lenz et al. 2000). Some of nematode's sp. that infect termites are listed in Table 3.

Table 3. Nematode species parasitic to termites

S. No.	Nematode Species	Termite species affected	References
1.	<i>Heterorhabditis sonorensis</i>	<i>Macrotermes bellicosus</i>	Zadjiet al. (2014a, c)
2.	<i>Steinernema</i> sp.	<i>Trinervitermes occidentalis</i> and <i>Macrotermes bellicosus</i>	Zadjiet al.(2014b)
3.	<i>Steinernema carpocapsae</i>	<i>Odontotermes obesus</i>	Divya and Sankar (2009)
4.	<i>Steinernema glaseri</i>	<i>Reticulitermes flavipes</i>	Murugan and Vasugi (2011)
5.	<i>Steinernema feltiae</i>	<i>Reticulitermes</i> sp.	Mauldin and Beal (1989)
6.	<i>Steinernema longicadam</i>	<i>Odontotermes formosanus</i>	Zhu (2002)
7.	<i>Heterorhabditis bacteriophora</i>	<i>Reticulitermes</i> spp. <i>Heterotermes aureus</i> (<i>Gnathamitermes perplexus</i>)	Yu et al. (2006)
8.	<i>Steinernema ribobrave</i>	<i>Coptotermes heimi</i>	Yu et al. (2006)
9.	<i>Neosteinerinema longicurvicauda</i>	<i>Reticuldermes flavipes</i>	Nguyen and Smart (1994)
10.	<i>Chroniodiplogaster aerivora</i>	<i>Coptotermes</i> and <i>Nasutitermes</i>	Merrill and Ford (1916)
11.	<i>Diplogaster labiates</i>	<i>Coptotermes formosanus</i>	Pemberton (1928)
12.	<i>Heterorhabditis baujardi</i>	<i>Heterotermes indica</i>	El-Bassiouny and El-Rahman (2011)
13.	<i>Pseudaphelenchus yukiae</i>	<i>Cylindrotermes macrognathus</i>	Kanzakiet al. (2009b)
14.	<i>Pseudaphelenchus vindai</i>	<i>Microtermes exiguous</i> , <i>Amitermes beaumonti</i>	Kanzakiet al. (2010)
15.	<i>Termirhabditis fastidiosus</i>	<i>Reticulitermes flavipes</i>	Massey (1971)
16.	<i>Rhabditis rainai</i>	<i>Coptotermes formosanus</i>	Carta and Osbrink (2005)
17.	<i>Oigolaimella attenuata</i>	<i>Reticulitermes</i> spp.	von Lieven and Sudhaus(2008)
18.	<i>Poikilolaimus carsiops</i>	<i>Neotermeskoshunesis</i>	Kanzakiet al. (2011)
19.	<i>Poikilolaimus floridensis</i>	<i>Cryptotermes cavifrons</i> , <i>C. brevis</i> , <i>Reticulitermes flavipes</i> and <i>Coptotermes formosanus</i>	Kanzakiet al. (2009a)
20.	<i>Poikilolaimus ernstmayri</i>	<i>Reticulitermes lucifugus</i>	Sudhaus and Koch (2004)
21.	<i>Peloderatermitis</i> sp.	<i>Anacanthotermes turkestanicus</i>	Carta et al. (2010)
22.	<i>Hartertiagallarum</i>	<i>Coptoteremes</i> sp.	Watson and Stenlake (1965)
23.	<i>Caenorhabditis</i> sp.	<i>Anacanthotermes turkestanicus</i>	Handoo et al. (2005)

In India, *Steinernema carpocapsae* has been shown to be effective against *Odontotermes obesus*, one of the major termite pests in agricultural areas (Divya & Sankar, 2009). Similarly, *Steinernema glaseri* has demonstrated its pathogenic potential against *Reticulitermes flavipes* in India (Murugan & Vasugi, 2011), and *Heterorhabditis bacteriophora* has been found to affect *Reticulitermes* spp. and *Heterotermes aureus* (Yu et al., 2006). These nematodes are particularly effective under laboratory conditions, but environmental factors such as soil moisture and temperature significantly influence their success. Comparatively, studies in other parts of the world have yielded interesting results. For example, *Heterorhabditis sonorensis* has been effective against *Macrotermes bellicosus* in Africa (Zadjiet al., 2014a, c), while *Steinernema* sp. has shown promise in controlling *Trinervitermes occidentalis* and *Macrotermes bellicosus* (Zadjiet al., 2014b). *Steinernema longicadam*, effective against *Odontotermes formosanus* (Zhu, 2002), highlights the global applicability of this genus across different termite species. In addition, *Pseudaphelenchus yukiae* and *Pseudaphelenchus vindai* have been used in controlling *Cylindrotermes macrognathus* and *Microtermes exiguus*, respectively (Kanzaki et al., 2009b; Kanzaki et al., 2010), with similar findings from Indian studies on *Coptotermes* species.

3.3. Predators

Ants, beetles, flies, spiders, and wasps are attracted to termite carcasses because they are high in protein.

Birds (woodpeckers, starlings, and hornbills), frogs (African Bullfrog, African Reed Frog, African Tree Frog and Green Tree Frog), reptiles (lizards, including geckos and monitor lizards) and mammals (anteaters, monkeys, aardvarks, and some species of bats) are among the other predators of termites. *Lomamyialati pennis*, a berothid larva, lives on termites and feeds on them via a vapour-phase toxicant (Johnson et al., 1981). Because termites have such a good defence technique, as termites use soldier castes with strong mandibles and chemical defenses to protect their colonies, while also employing alarm pheromones, rapid nest sealing, camouflage, escape behaviors, and cooperative defense to deter predators and threats so only few predators can feast on them. As a result, natural predators aren't very good at controlling termite populations.

Predators like ants, beetles, flies, spiders, and wasps have limitations in termite control due to their inconsistent impact on large colonies and difficulty in targeting termites deeply nested within the soil or wood. Additionally, relying on natural predators may not provide immediate or sufficient control and can disrupt local ecosystems by altering predator-prey dynamics.

3.4. Bacteria

Bacterial infestations on termite colony have been shown to suppress them (Fig. 5). However, there has not been much research done in this field. Table 4 enlist a few of the bacteria that have been investigated.

Table 4. Bacterial species pathogenic to termites

S. No.	Bacterial Species	Termite species effected	References
1.	<i>Acinetobacter calcoaceticus</i>	<i>Coptotermes formosanus</i>	Osbrink et al. (2001a)
2.	<i>Citrobacter sp.</i>	<i>Microtermes beelsoni</i>	Harazono et al. (2003)
3.	<i>Bacillus thuringiensis</i>	<i>Nasutitermes ehrhardti</i>	Wang and Henderson (2013)
4.	<i>Bacillus subtilis</i>	<i>Macrotermes bellicosus</i>	Omoya and Kelly (2014)
5.	<i>Serratia marcescens</i>	<i>Coptotermes formosanus</i>	Osbrink et al. (2001b)
6.	<i>Rhizobium radiobacter</i>	<i>Odontotermes obesus</i>	Devi et al. (2007)
7.	<i>Rhizobium leguminosarum</i>	<i>Microtermes beelsoni</i>	Devi (2013)
8.	<i>Staphylococcus aureus</i>	<i>Bifiditermes beelsoni</i>	Khucharoenphaisan et al. (2012)
9.	<i>Pseudomonas fluorescens</i>	<i>Odontotermes obesus</i>	Devi and Kothamasi (2009)
10.	<i>Pseudomonas aeruginosa</i>	<i>Coptotermes formosanus</i>	Khucharoenphaisan et al. (2012)

Devi and Kothamasi (2009) explored the effectiveness of *Pseudomonas fluorescens* in controlling *Odontotermes obesus*, a major termite pest in India. Their research demonstrated that *Pseudomonas fluorescens* can significantly reduce termite populations, making it a viable biocontrol agent for managing infestations. Similarly, Devi et al. (2007) investigated the pathogenic effects of

Rhizobium radiobacter on *Odontotermes obesus*, showing promising results for its potential as a biological control method. Another study by Devi (2013) examined *Rhizobium leguminosarum* in controlling *Microtermes besoni*, indicating its possible use as an effective biocontrol agent in India's termite management practices.

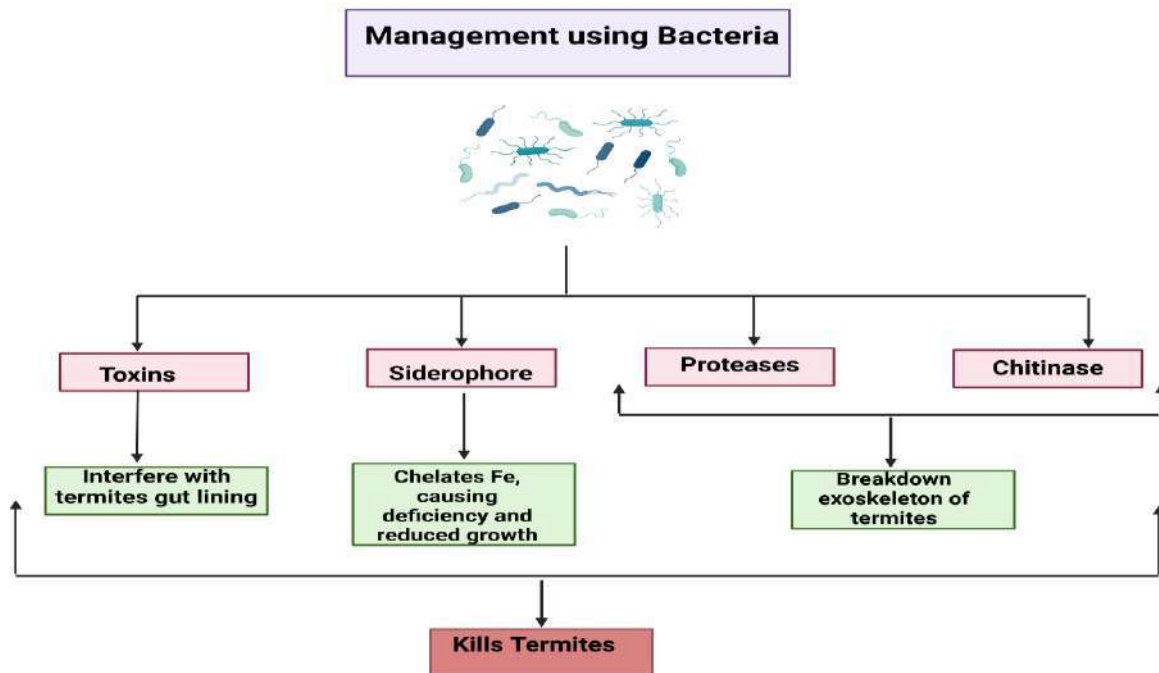


Fig. 5. Management of termites using bacteria

Bacterial infestations for termite control are limited by their specificity to certain termite species and susceptibility to environmental factors that can reduce their effectiveness. Additionally, ensuring the bacteria spread throughout and impact an entire colony can be challenging, especially in large or complex nests.

3.5. Green management

Environmentally-friendly pest management involving plants is often referred to as "green management," stands out as a superior approach due to its minimal impact on the environment. Laboratory experiments have demonstrated that numerous plants and their phytoconstituents possess toxicity or repellent properties against termites (Paul et al. 2018). In the context of preserving wooden structures, pre-treatment using locally available anti-termite plants or plant extracts has been touted as an effective strategy (Verma et al., 2009). Furthermore, certain grasses,

such as vetiver grass, are actively disliked and avoided by termites (Jayashree et al., 2013). Therefore, farmers can effectively deter termites from gardens and farms by cultivating such plant varieties. The anti-termite properties of various plants are comprehensively described in the chapter authored by Paul et al. (2018). Green management methods can be labor-intensive and require extensive knowledge of plant species and their interactions with termites. They may also face limitations in effectiveness against severe infestations or in diverse and large-scale environments, making them less practical for widespread termite control in India

4. Molecular Methods for Termite Management

4.1. RNA interference

Gene silencing through RNA interference (RNAi) has been introduced as an innovative approach to address

insect pest management, as demonstrated in studies (Vogel et al. 2019; Zhu and Palli 2020). RNAi is a highly conserved mechanism for post-transcriptional, sequence-specific gene silencing, initiated by the introduction of double-stranded RNA (dsRNA), as highlighted by Zotti et al. (2018). The pioneering application of RNAi in *Reticulitermes flavipes* involved the silencing of endogenous hexamerin and cellulose genes (Zhou et al. 2006a and 2006b). This method has been successfully employed to silence approximately 16 genes in termites and their symbiotic protozoa, as documented (Scharf, 2015).

In a groundbreaking study by Wu et al. (2019), they targeted the conserved region of five endoglucanase genes from *Coptotermes formosanus* (CfEGs) using both dsRNA injection and oral delivery methods. RNAi resulted in significant gene silencing of CfEGs, leading to termite mortality due to reduced enzyme activity and decreased weight compared to control worker termites. Notably, the silencing of genes associated with chitin synthase B and a putative peritrophin linked to the peritrophic matrix of *R. flavipes* heightened the susceptibility of *R. flavipes* to termiticides and bacterial pathogens (Sandoval-Mojica and Scharf, 2016). Moreover, increased susceptibility against *Metarhizium anisopliae* was observed in *R. flavipes* following the silencing of genes responsible for producing Termicin and GGBP2 proteins, suggesting the importance of these

proteins in fungal disease resistance in termites (Hamilton and Bulmer, 2012). These findings imply the potential development of RNAi-based termiticides in the future.

4.2. Paratransgenesis

Paratransgenesis, a technique in which microorganisms, such as viruses, fungi or bacteria (symbionts in case of termites) are used as gene-drive and expression vehicles in a host organism (Husseneder and Collier 2008). In this technique genetically engineered symbionts are used as carriers of lethal genes or toxins in termite which can affect various defense or physiological systems in termites (Chouvenec et al. 2011) Husseneder et al. (2009) has patented the use of paratransgenesis to control termites or other social insects. Genetically engineered *Trabulsiella odontotermis* a termite-specific bacterium can act as efficient carrier for spreading gene products through paratransgenesis in termite colonies (Tikhe et al. 2016).

Molecular control methods like RNA interference and paratransgenesis face downsides in India due to their high cost, technical complexity, and potential environmental risks. Additionally, these approaches require extensive research and regulatory approvals, which can be challenging to navigate and implement effectively on a large scale.

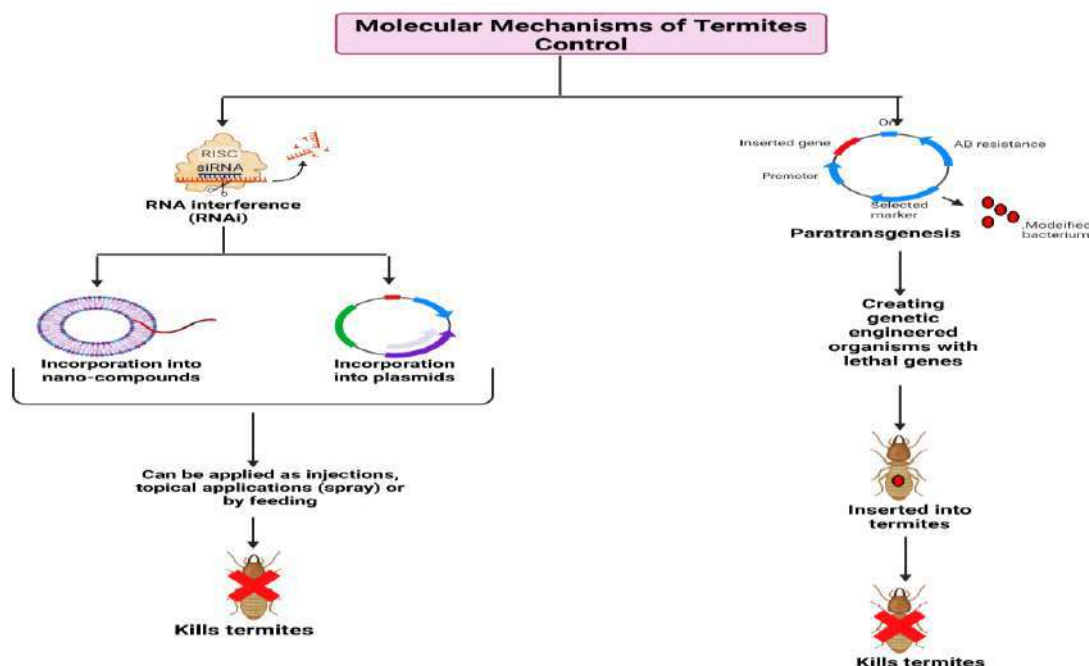


Fig. 6. Molecular tool for termite management

5. Challenges associated with Termite management in India

India boasts a rich array of termite species, encompassing both subterranean and drywood termites (Mahapatro et al. 2018; Sharma et al., 2021). This extensive diversity poses a formidable challenge in formulating a universal approach to termite control. Despite meticulous installation and treatment, subterranean termites are responsible for nearly 95% of structural damage (Kuswanto, et al.2015), often exploiting concealed entry points that necessitate the discerning eye of trained experts for detection. The safe and efficacious treatment of termite infestations requires the expertise of seasoned technicians.

Regrettably, there exists a significant dearth of public awareness regarding indicators of termite infestations, preventive measures, and management practices in India. This lack of awareness frequently results in delayed responses and inadequate termite management, permitting infestations to persist and escalate damage. In the Indian context, insufficient emphasis on the technical aspects of termite management, and insufficient research on insecticide resistance developing mechanisms in termites has emerged as a principal reason for mismanagement (Mahapatro, 2017). Furthermore, the accessibility of professional pest control services and well-trained technicians remains limited, particularly in rural areas. The inadequacy of infrastructure and resources dedicated to termite management further impedes the implementation of effective control strategies and timely interventions.

CONCLUSION

Termite management is currently a challenge for the scientific community. While several ways to manage termite populations have been tested, every solution has some or other downsides. The use of certain termiticides has been linked to significant dangers to human health as well as the environment. There are a variety of biological control agents available, but none of them are believed to be 100% effective on their own. There is an urgent need of developing a mechanism to identify the damage causing termites species-wise, system for monitoring and record keeping and regular sampling or inspections of termites and damage caused by them so as to warrant

a proper management action. In conclusion, this study underscores the critical need for an integrated termite management strategy in India. By adopting a comprehensive and sustainable approach, it is possible to reduce economic losses, preserve ecosystems, and promote resilient agricultural and urban systems. Implementing such strategies will require coordinated efforts, policy support, and continued research to optimize termite management practices in India and ensure long-term sustainability.

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HOW TO CITE: Radhika Sharma, Neha Rana, Reshma Sinha*, Asha Poonia, Ramneek Kaur, Challenges And Opportunities In Termite Control: An Indian Perspectives, *Int. J. Sci. R. Tech.*, 2026, 3 (4), 721-738. <https://doi.org/10.5281/zenodo.19661822>