Review

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Biological Control Strategies for Termite Management

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Review

Biological Control Strategies for Termite Management

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Abstract: Termites are eusocial arthropod decomposers that increase crop productivity and soil fertility. Because of the various benefits they possess, they are being exploited by humans. Termite infestations cause significant damage to structures and ecosystems. There are various physical and chemical methods for termite removal and control, but the use of chemical insecticides has a detrimental effect on human health and the environment, so efforts are directed towards the development of biological approaches to reduce their presence. Various effective and dependable biological approaches focused on using bacteria, fungi, and viruses have been explored, but termites continue to pose a major global threat. Recent advancements in molecular biology may provide a better solution for termites control. This review summarizes various biological methods to reduce the presence of termites in a sustainable manner.

Keywords: termites; pests; biocontrol; suistanable

1. Introduction

Termites (order Isoptera) are detriphagous eusocial pests that can cause detrimental effect to wooden infrastructure, buildings, crops, and forestry plantations. Despite their positive contribution to nutrient cycling via organic matter decomposition, improving soil fertility, water infiltrability, providing food and biofuel sources, termites are commonly known as economical pests (Figueirêdo et al., 2015; Siddiqui et al., 2023; Aidoo et al., 2023; Muon et al., 2023).

Annually, termites account for a global economic loss of USD 50 billion (Subekti et al., 2015). Over 3000 species of termites are known to exist today throughout the world.

According to Subekti et al., 2015, the USA has identified 50 species, of which 20 are classified as structural pests. In India, 337 species have been documented, of which 35 are known to cause harm to structures and agricultural products (Murthy et al., 2015). Termites are often classified into four types on the basis of their habitat and behaviour: subterranean, drywood, dampwood, and formosan. According to Rust and Su, 80% of the total damage is caused by subterranean termites.

To address these challenges, many physical and chemical termite management strategies are utilized around the world, but bulk of them rely on the use of chemical termiticides. However, excessive use of chemical insecticides has a negative influence on human life, animal health and non-target creatures such as beneficial insects and pollinators, as well as soil micro and macrofauna (Liu et al., 2011). Furthermore, the indiscriminate use of these chemical insecticides contributes to the emergence of insecticide resistance to bifenthrin, fipronil, cypermethrin, and deltamethrin, as well as soil and groundwater contamination, resulting in toxic residues being retained and bioaccumulated in the food chain for a long time. Thus, there is an urgent need to develop sustainable and environment friendly termite control methods as an alternative to chemical methods.

In recent years, the use of plant extracts and natural antagonists like fungi and bacteria as biocontrol agents (BCAs) has garnered significant interest as a sustainable termite management strategy. Nowadays, RNA interference (RNAi) has become a viable option for creating biological control tactics since it offers superior target-specificity for many species. Biological alternatives are

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highly efficient, inexpensive, safer for humans and create no pollution in the environment. An overview of the various biological agents used to combat termites is provided in this review.

2. Termites as a Noxious Agricultural and Industrial Economic Agent

Termites are the primary decomposers of dead plant materials and they significantly contribute to soil nutrient turnover. When termites feed on buildings, electric cables, agriculture crops or plant materials used by humans, they act as noxious pests (Scharf et al., 2015; Wekhe et al., 2019; Azam et al., 2015). Termite management and economic losses cost hundreds of millions of dollars annually worldwide, as demonstrated in Figure 1

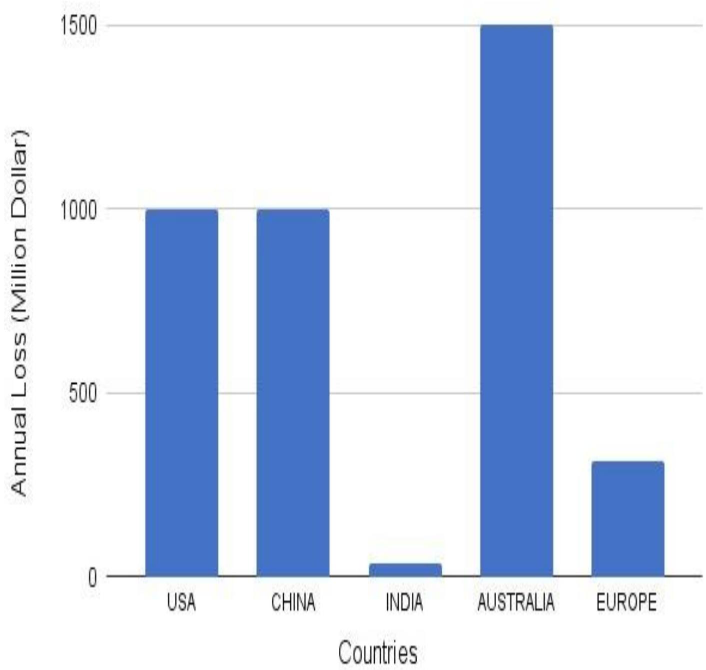

Figure 1. Loss caused by termites annually (Source: This study).

Figure 2. Most attacked states by Termites in India (Source: This study).

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According to Smagghe, the world population is predicted to reach over 9 billion by 2050, which would also lead to 70% increase in agricultural and food output. Termites are highly destructive pests that attack various annual and perennial crops. Various crops damaged by termites in India are shown in Table 1.

Table 1. Crops yield reduction caused by Termites.

Agriculture Crops	Termites	Yield Loss (%)	Place	Symptoms of Damage	Year	References
Wheat	*Cryptotermes heimi, Odontotermes obesus, O. redemanni, M obesi, O. feae, T. biformis*	43%-80%	Rajasthan, Madhya Pradesh, Bihar, Delhi, Punjab, Madhya Pradesh, Andhra Pradesh, Gujarat, Maharashtra, Karnataka, Haryana, Kerala and Tamil Nadu	Affected plants dry up completely and may give rise to white ears	1995 - 2016	Farook et al., 2019 Sharma et al., 2004
Maize	*O. obesus, M. obesi*	30% - 75%	Rajasthan, Madhya Pradesh, Haryana, Punjab	From seedling emergence to ear growth, termites target every stage of the maize crop	1984-2010	Parween et al., 2016 Rana et al., 2021
Pulses	*Odontotermes obesus, Odontotermes parvide*	25%-90%	Rajasthan, Madhya Pradesh, Haryana, Punjab	Bore holes on buds, flowers or pods Silvery patches and streaks on leaves	1990-2012	Paul et al., 2018
Groundnut	*Microtermes spp., Odontotermes* spp., *Amitermes* spp., *Microtermes* spp., *Odontotermes* spp.	15%-30%	Punjab, U.P., Rajasthan, Delhi, Haryana, Karnataka, Gujarat, M.P., Maharashtra, Kerala	Root and stem hollowing Pod bore holes	1984-2012	Paul et al., 2018
Soyabean	*M. albopartitus, M. redenianus, A. latinotus, A. tenax*	20%-25%	Punjab, Haryana	Stem lesions, Wilted or curled leaves	1980-2012	Paul et al., 2018
Coconut				Yellowing of leaves		

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	Microtermes spp., *Microcerotermes* spp., *Coptotermes* spp.	20%-30%	Western coast of India	Stunted growth	1990-2016	Paul et al., 2018
Sugarcane	*Odontotermes redemanni*	74 %	Punjab, Haryana	Yellowing and wilting of leaves	1986-2015	Parween et al., 2016
Tea	*M. beesoni*	11%- 55 %	North East India	Galls on the roots affecting nutrient uptake Shoot growth is retarded and photosynthetic rates may decrease	1980-2016	Roy et al., 2020
Chilli Pepper	*O. obesus* and *M. obesi*	45 %	Rajasthan	Infested leaves develop crinkles and curl upwards Elongated petioles (leaf stalks) Buds become brittle and may drop down. Early-stage infestations lead to stunted growth	1984-2012	Parween et al., 2016
Cotton	*M. mycophagus, O. obesi*	25%	Rajasthan, Gujarat, Haryana, Punjab and Madhya Pradesh	**Drying and drooping of terminal shoots** Shedding of squares (immature flower buds) and young bolls (developing cotton capsules).	1980-2014	Parween et al., 2016

Termites are the leading cause of wood decay in the natural environment. *Heterotermes indicola* is the primary subterranean termite in India that impact buildings and other infrastructure (Mahapatro & Chatterjee, 2018). According to recent studies, *Heterotermes indicola* caused 90% of instances of substantial damage to timber structures between 2009 and 2021 in a variety of areas, including Chandigarh, Delhi, Haryana, Jammu & Kashmir, West Bengal, Punjab, and Orrisa.

In India, it was also discovered that termites were attacking river dams present in the vicinity of Hirakund dam on the Mahanadi River in Orissa. Mahapatro & Chatterjee, 2018 stated that termites also damaged a whole village in Rajasthan near Kota. A very recent report from the Times of India reported that in U.P., termites devoured around Rs. 18 lakhs that were kept in a Bank of Baroda.

Different types of drywood and subterranean termites invaded botanical gardens, museums, and libraries in tropical regions. Drywood termites, such as Cryptotermes and Kalotermes, have been seen to live in books and paper stacks and dig tunnels under timber constructions (Nagaraju et al., 2021). Twenty percent of homes have termite damage, according to Kalleshwaraswamy et al., 2023. Nine termite species belonging to the families

Rhinotermitidae, Termitidae, and *Kalotermitidae* were responsible for 89% of the termite infestation in historic buildings and 62% of the infestation in residential buildings in India (Mello *et al.*, 2014; Gusmao et al., 2014).

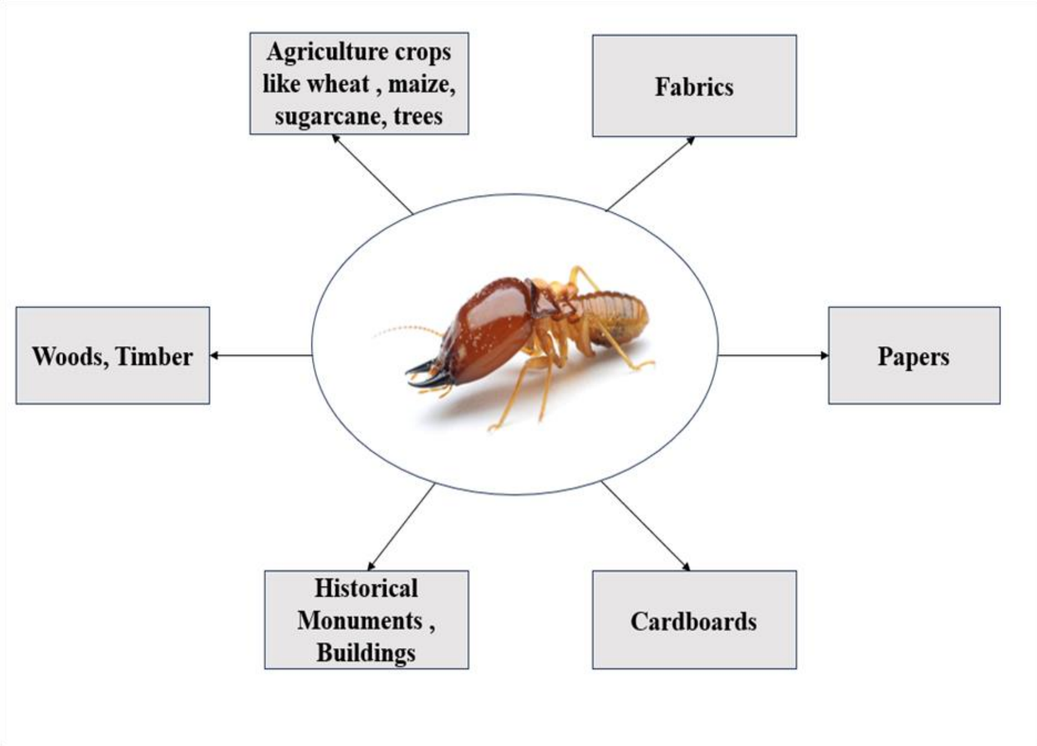

Figure 3. Damages inflicted due to termites (Source: This study).

3. Management of Termites

In recent decades, a number of approaches for managing termites in diverse fields have been developed. Traditional termite treatment methods include physical and chemical treatments.

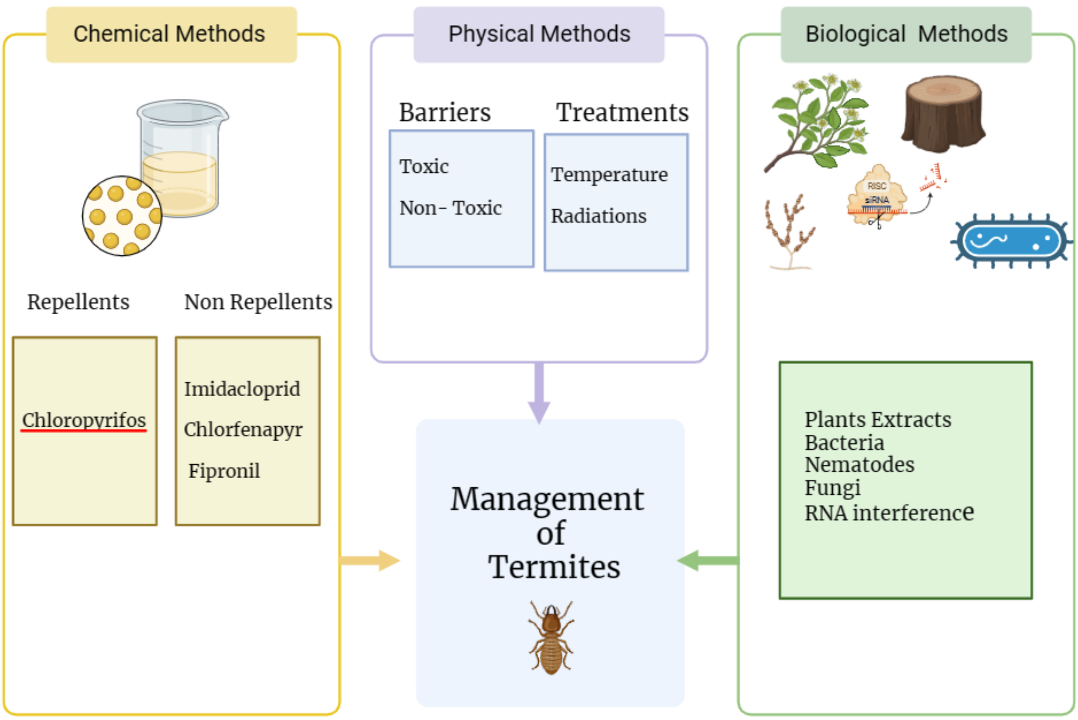

Figure 4. Different approaches of Termites control (Source: This study).

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3.1. Physical Methods

Physical methods of termite removal involve the dequeening or removal of kings from the colony (Atsbha & Hintsa, 2018), the incorporation of materials like sand etc., freezing, heating, and the use of microwave radiation. Humidity also led to the removal of termites (Cao et al., 2016).

Incorporation of fine materials like sand crushed volcanic cinders, gravel aggregate, and Termi-Mesh, a tiny mesh constructed of stainless steel, has the ability to operate as a barrier against subterranean termites (Li et al., 2017). Several limitations of physical approaches have been identified, including their inability to eliminate termites quickly, the cost and time required to create physical barriers, and the need for regular inspections and maintenance.

3.2 Chemical Methods

The major way of managing subterranean termites is to treat the soil with chemical insecticides near the active infestation. Chemical barriers fall into two categories: repellent and non-repellent. Toxicity in non-repellents cannot be detected in advance, therefore the lethal impact is passed on to successive colony members (Ahmed et al., 2006). Non-repellent termiticides include chloranthraniliprole, imidacloprid, chlorfenapyr, and fipronil. Termites may detect the repellent compounds chlorpyriphos, bifenthrin, and permethrin and relocate away from the treated area, preventing toxicity transfer to other colony members (Iqbal and Saeed, 2013). Chlorpyrifos 20 EC is sprayed in various crops like groundnut, maize, sugarcane, and also in soil for effective termite management.

Chemical fumigation is also used to control drywood termite infestations. Methyl bromide phosphine, carbon dioxide and sulfuryl fluoride are the active components in several fumigants. Methyl bromide is a frequently employed fumigant. It damages insects' nervous system and penetrates swiftly and profoundly at room pressure.

Chemical pesticides were used as a preventative approach to offset the losses brought on by pests and other insects, but their widespread usage had deadly effects all over the world, including diminished soil fertility, low productivity of land air, and water pollution, and threats to human health (Liu et al., 2011). As environmental preservation and safety become more and more important, these chemical termite control products will soon be phased out and replaced by biopesticides.

3.3. Biological Warfare Against Termites

Biological termite control uses natural antagonists such as bacteria, viruses, fungi, and nematodes instead of man-made chemical pesticides, which can be harmful to human health and the environment. Many plants produce biologically active compounds, and molecular approaches such as RNA interference (RNAi) can be used to control termites. RNA interference is a biological mechanism that is conserved in eukaryotes, including insects, in which mRNA degradation and protein synthesis disruption turn off gene function (Zhu & Palli, 2020). As a result, biological management has several advantages, as it is a sustainable, environmentally friendly technique, cost-effective, reduces health risks, and improves crop quality.

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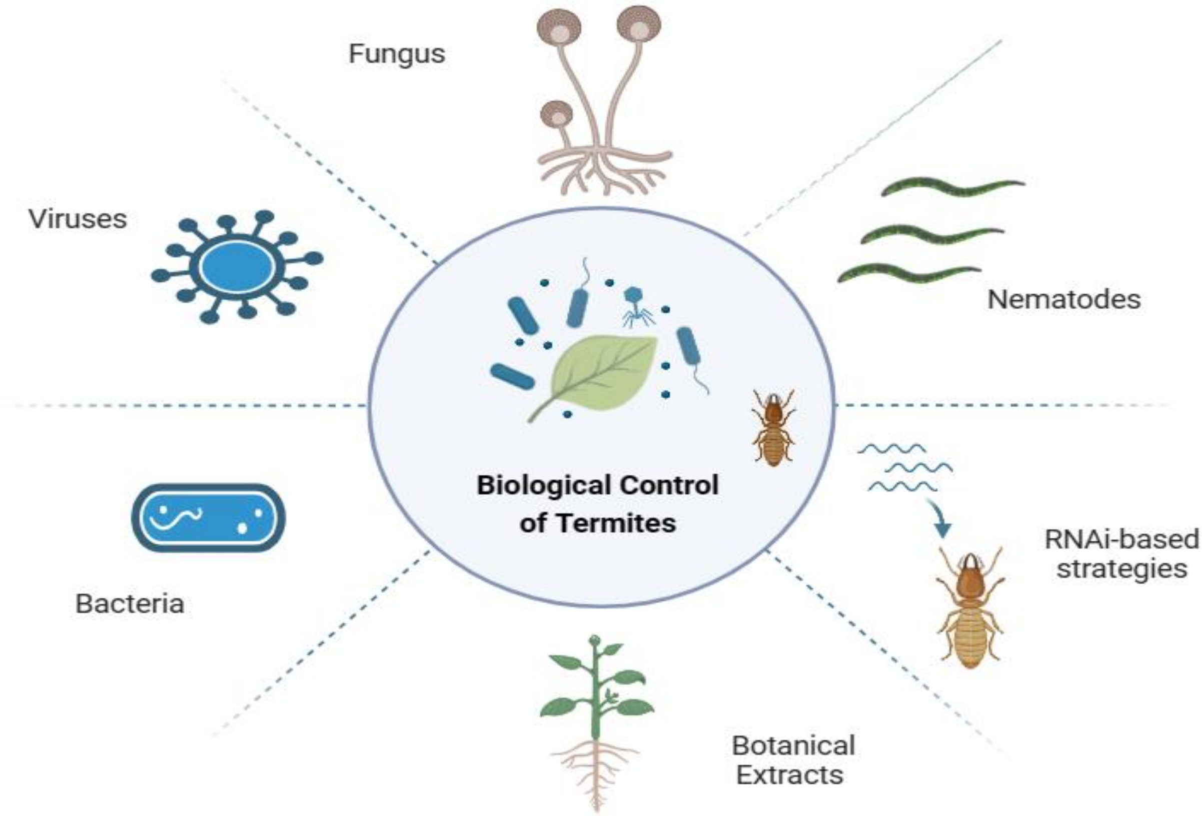

Figure 5. Biocontrol of Termites (Source: This study).

3.3.1. Plant Extracts for Termite Management

Botanicals are phyto-based products that are seen to be the most promising substitutes for chemical pesticides. They are generated from plant stems, roots, leaves, fruits, flowers, seeds, and wood. Pesticidal activity is found in around 2000 plant species from 60 families, and many of them are exploited as insect repellents, attractants, growth regulators, behavior modulators, and so on (Verma et al., 2018). Chemicals, such as terpenoids, flavonoids, and saponins, or combinations of chemicals, are naturally found in plants and can repel and kill termites, as well as disrupt their gut flora.

Pre-treating building materials such as wooden frames, pillars, logs, and timbers with anti-termite herbal products like *Datura alba, Ricinus communis, Curcuma amada, Cannabis sativus,* and *Asafoetida* spp. in areas afflicted by termites has proven effective in India. However, more research is necessary to determine the effectiveness of these remedies in treating soil and preventing subterranean termite infestations. Plants are safer for the environment, biodegradable, and non-toxic, even though they are less effective than chemicals.

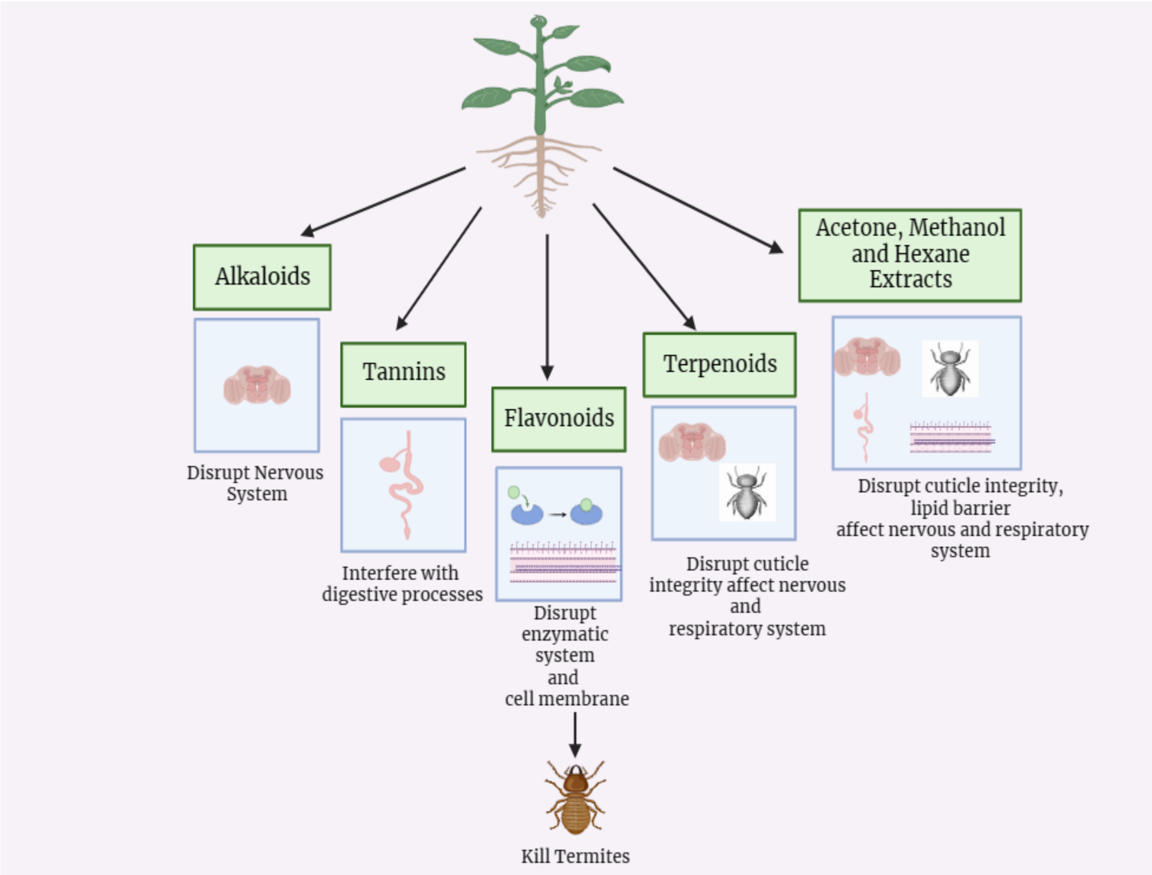

Figure 6. Termites control via plants secondary metabolites (Source: This study).

Table 2. Management of Termites using Plants extracts.

Sr. No.	Plants Species	Parts	Active compounds	Mechanism	Mortality Rate	Country	References
1	*Cymbopogon citratus*	Leaves	Alkaloids, Flavonoids, Phenolics, Tannins, Saponins, Glycosides and Citrals	Disrupt cell membrane and cytoskeleton structure Cause blockage of neuromuscular junction and respiratory failure	75%	Africa	Essien et al., 2023
2	*Dioscorea bulbifera*	Leaves	Methanolic extracts	Inhibit enzymatic activity and affect the metabolism of termites	70.97%	Indonesia	Oksari et al., 2023
3	*Rhazya stricta,*	Leaves	n- hexane extracts	Disrupt nervous system	70-76.3%	Saudi Arabia	Alshehry et al., 2014

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	Lantana camara, Ruta chalepensi and *Heliotropium bacciferum*		(Ethyl ester, Octadecadienoic acid)	Interfere with metabolic pathways			
4	` *Azadirachta excelsa*	Seed Kernel	*n*-hexane (Hexadecanoic acid, Ethyl ester, Octadecadienoic acid) and methanolic extracts	Disrupt the growth, reproduction and hormonal regulation of termites	80%	Indonesia	Adfa et al., 2023
5	*Lavandula latifolia, Origanum vulgare* and *Syzygium aromaticum*	Dry Buds	*Lavandula latifolia* (Linalool, Lavandulol, *β*-terpinyl acetate) *Origanum vulgare* (Thymol, *m*-cymene, Linalool and Terpinen) *Syzygium aromaticum* (Eugenol)	Affect nervous system	75%	Egypt	Salem et al., 2020
6	*Odontotermes assamensis*	Oil	Eugenol, *α*-pinene, terpinen-4-ol and *β*-*trans*-caryophyllene	Affect nervous system and other physiological process like digestion, respiration	70-90%	India	Pandey et al., 2012
7	*Syzygium aromaticum*	Oil	Flavonoids, Glycosides, Tannins and terpenoids	Affect feeding behaviour of termites by inhibiting enzymes essential for digestion also alter smell and taste of food Blockage of neuromuscular junction	100%	Africa	Sadiq et al., 2019
8	*Carica papaya*	Leaves	Papain enzyme, Saponins, Flavonoids and Alkaloids Karpain	Proteolytic action of papain disrupt internal proteins affect digestive processes	40%	Malaysia	Zahtamal et al., 2017

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				Disrupt cell membrane, leading to cell leakage, also affect nervous system			
9	*Eucalyptus globulus*	Leaves	Ethanolic Extracts	Disrupt social organization of termite colony Also interfere with termite nervous system, digestive and respiratory processes	90%	India	Kaundal et al., 2023
10	Bintaro	Seeds	Quercetin	Has antioxidant activity may influence cellular processes, interfere with cell cycle	80%	Japan	Tarmadi et al., 2014
11	*Azadirachta indica*	Oil	Azadirachtin	Disrupt foraging, social behaviour, antifeedant properties and also impact reproductive capability	74%	Japan	Himmi et al., 2013
12	*Cissus quadrangularis, Pennisetum purpureum, Vetiveria zizanoides*	Leaves	Acetone and Hexane extracts	Disrupt cuticle, neural transmission, has antifeedant properties, interfere with chitin synthesis	90%	Africa	Kasseney et al., 2016
13	*L. leucocephala, A. paniculata, A. indica* and *P. niruri*	*Leaves*	Flavonoids and Methanolic extracts	Antioxidant properties lead to disruption of oxidative	70-100%	Malaysia	Bakaruddin et al., 2018

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	balance, disrupt cellular membranes and nervous system	

3.3.2. Management of Termites using Bacteria

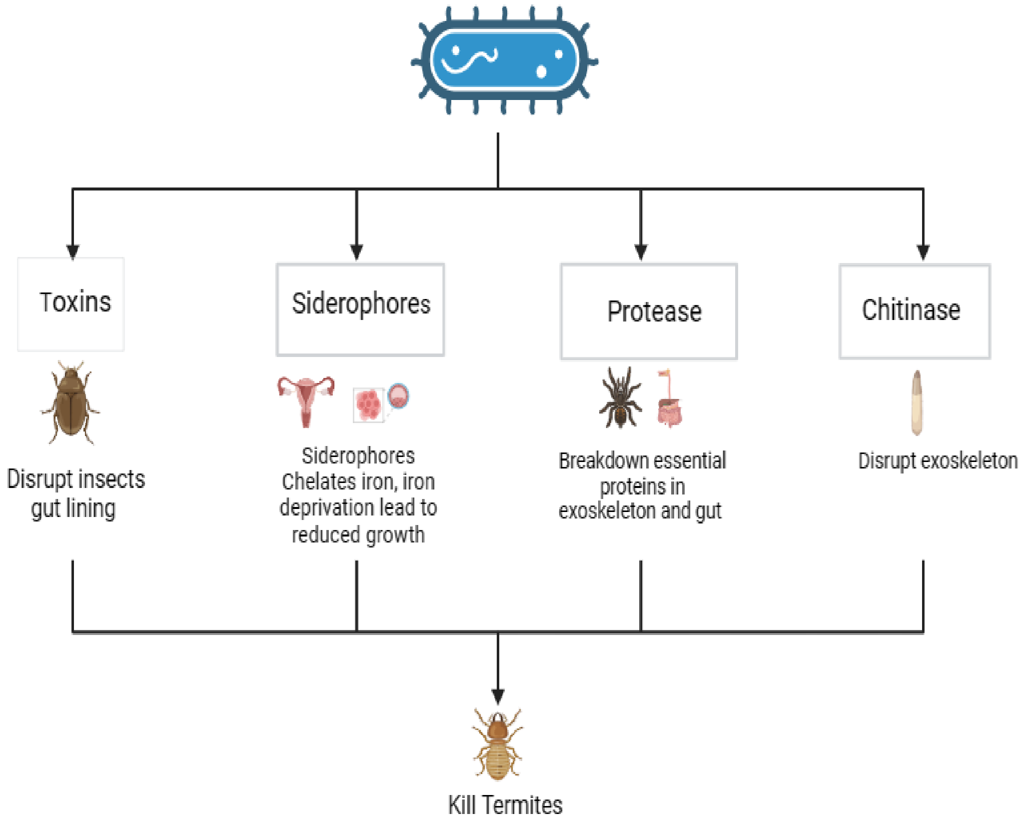

Figure 7. Bacterial compounds as an effective biocontrol for termites (Source: This study).

Bacterial pathogens were the first microorganisms to be tested as a biological control agent against various rural nuisances. According to Kalha et al., 2014, the majority of bacteria used for biocontrol are found in the families *Enterobacteriaceae, Streptococcaceae, Pseudomonadaceae*, and *Bacillaceae.*

Over 80% of termites (*Microtermes obesi* and *Microcerotermes beesoni*) are killed by *Bacillus thuringiensis* subsp. israelensis, making it a very efficient pathogen against termites. *Bacillus thuringiensis* produces a crystal-clear protein that is toxic to termites and other insects. When these toxins enter the termite's digestive system, they become active due to the alkaline condition of the insect's gut. These toxins disrupt the termite's gut lining, leading to starvation or infection and eventually, death. *Bacillus licheniformis* PR2 has been found to produce chitinase and protease activity up to 82.3 units/mL and 35.9 units/mL, respectively. These activities resulted in setae loss, epicuticle disintegration, procuticle rupturing, and socket enlargement in *Reticulitermes speratus* (Moon et al., 2023).

Some antagonistic bacteria inhibit the growth of termites by producing secondary metabolites like hydrogen cyanide. In addition to producing HCN, *P. fluorescens* also inhibits the termite respiratory chain's Cytochrome C Oxidase enzyme, killing *Odontotermes obesus* (Devi et al., 2009).

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Table 3. Entomopathogenic bacteria as a biocontrol for termites.

Bacteria	Termites	Enzyme formulations	Mode of Action	Country	Mortality Rate	References
Stentrophomons maltophilia	*Coptotermes heimi* and *Heterotermes indicola*	Chitinase	Disruption of cuticle	Pakistan	53 %	Jabeen et al., 2018
Methicillin Resistant *Staphylococcus aureus*	*Reticulitermes flavipes*	Protease	Alter haemolymph protein that affect cellular immune response, Disrupt essential processes like digestion, respiration	Korea	70%	Zeng et al., 2016
Serratia marcescens (SM1)	*Odontotermes formosanus* (Shiraki)	Chitinase enzymes	Hydrolyzes chitin in locust midgut and perforates intestinal membranes, making insecticidal proteins more likely to penetrate the insect body and destroy the digestive tract	China	NA	Fu et al., 2020
Rhizobium radiobacter, Alcaligenes latus, Aeromonas caviae	*Odontotermes obesus*	HCN production	Disrupt electron transport chain and preventing cells from utilizing oxygen	India	70% mortality followed by 1 hr incubation	Devi et al., 2007
Serratia marcescens	*Odontotermes formosans*	Protease	Cuticle damage, disrupt microbial	China	80 % mortality after 72 hours	Fu et al., 2020

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			balance in termite gut			
Entrobacter cloacae	*Odontotermes obesus*	Insecticidal Proteins	Affects the cellular immune response	China	NA	Zhang et al., 2010
Citrobacter freundii	*Coptotermes* spp.	Cellulase Enzyme	Breaks cellulose present in cell wall so disrupt cuticle	Africa	NA	Omoya and Kelley, 2014
Bacillus licheniformis PR2	*Reticulitermes speratus kyushuensis* Morimoto	Chitinase	Cuticle degradation	Korea	88.9% after 3 hours	Moon et al., 2023
B. licheniformis USMW10IK	*G. sulphureus*	Chitinase	Cuticle degradation	Malaysia	22.8% after 48 h	Hussin and Mazid, 2020
Pseudomonas fluorescens CHA0	*O. obesus*	Cytochrome C Oxidase enzyme	Inhibit respiratory chain	India	NA	Devi et al., 2009
B. thuringiensis subsp. *israelensis*	*Microtermes obesi* and *Microcerotermes Beesoni*	Chitinase	Cuticle degradation	India	80% mortality	Singha et al., 2010; Wang & Henderson, 2013
Bacillus thuringiensis KJ3P1	*Macrotermes gilvus*	Chitinase	Cuticle degradation	Indonesia	50% after treatment	Pujiastuti et al., 2021

3.3.3. Fungal Species as a Biocontrol Agent for Termites

Entomopathogenic fungi plays a vital role in biological pest control and can cause mortality at all stages of development. The pathogenesis of termite fungal diseases appears to involve the following phases. Conidium first attaches and penetrates the insect cuticle, causing the germination of fungal hyphae in the haemocoel and production of toxins, which ultimately leads to termite death.

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Several EPF strains, including *Beauveria* spp., *Metarhizium* spp., and *Lecanicillium* spp., were evaluated against several insect pests and shown to be efficient termite biocontrol agents (Pandey et al., 2013). The Metarhizium and Beauveria genera have parasitic interactions with insects like termites.

Yii et al., 2015 used fipronil termiticide in combination with *M. anisopliae* spores to control *Coptotermes curvignathus*. They concluded that combining conidia with sublethal fipronil kills *C. curvignathus* in more than 99% of cases. In Iraq, a commercial formulation of the fungus *Metarhizium anisopliae* was used successfully to protect olive trees from termite species such as *M. diversus* (Hussain et al. 2011, Zaidawi et al., 2020). Table 4 shows a list of common fungal species that are harmful to termites.

Numerous studies have demonstrated the effectiveness of entomopathogenic fungi as biological control microorganisms for agricultural termite management, although fewer have demonstrated their ineffectiveness. Liu et al., 2019 observed that termites have highly sophisticated multidefence tactics against fungi. Their defence mechanisms include avoiding fungal-contaminated areas, secreting antifungal substances and using symbiotic bacteria as the foundation of their nests to prevent infections from entering their colonies. The dispersal, transmission, germination, penetration into the host, and environmental factors all contribute to the efficacy of fungal biocontrol (Yii et al., 2015). Fungus-based termite management can be a successful IPM program tactic as a result of these parameters being optimized.

Table 4. Fungal species pathogenic to termites.

Fungal Species	Termites	Mortality rate	LD_{50}	Country	References
Aspergillus spp.	*Microcerotermes beesoni Snyder*	55 %	3.69×10^7 conidia/ml	India	Pandey et al., 2013
Beauveria bassiana	*Microtermes obesi Holmgreen*	50%	2×10^5 conidia /ml	India	Singha and Dutta,2011
Isaria fumosorose	*Coptotermes formosanus*	100%	Not Known	Malaysia	Jessica et al., 2019
Metarhizium anisopliae	*Coptotermes formosanus*	62.8%	2.5×10^4 conidia /ml	USA	Wright et al., 2008
Metarhizium anisoploae	*Odontotermes formasanus*	100%	3×10^8 conidia/ml	USA	Dong et al., 2007
Metarhizium brunneum Cb15-III	*Odontotermes formasanus*	100%	1×10^8 conidia /ml	Kenya	Ambele et al., 2020
Aspergillus auricomus	*Coptotermes curvignathus* Holmgren	NA	1.49×10^5 conidia/ml	India	Kamarudin and Lau, 2022

Metarhizium anisoploae	*Coptotermes curvignathus*	95%	1×10⁷ conidia/ml	Malaysia	Samsuddin et al., 2016
M. anisopliae, *B. bassiana* and *A. niger*	*Psammotermes hypostoma*	61.52, 35.54 and 20.06%	4×10⁶ spores/ml	Egypt	Somalian et al., 2019
Metarhizium spp. B2.2	*Coptotermes* spp.	100%	8.3 x 10⁹ conidia/ml	Indonesia	Zulfiana et al., 2020
Metarhizium anisopliae	*Microtermes obesi* (Holmgren)	90%	2 × 10⁷ conidia/ml	India	Deka et al., 2021
Isaria farinosa	*Nasutitermes cornige*	85%	6.6 × 10⁴ conidia/ml	Brazil	Lopes et al., 2017
Paecilomyces fumosoroseus	*Coptotermes* sp.	NA	NA	USA	Dunlap et al., 2007
Beauveria bassiana	*Microtermes obesi*	25-40%	4 ×10⁶ conidia /ml	India	Padmaji and Kaur 2001
Metarhizium anisopliae TK29	*Coptotermes formosanus*	75%	1 × 10⁸ conidia/ml	China	Keppanan et al., 2018

3.3.4. Nematodes Species as Biological Control for Termites

A significant amount of termite's population is naturally killed by roundworms belonging to the phylum *Nematoda*. Four nematode families have the potential to control termites *Heterorhabditidae, Allantonematidae, Steinernematidae,* and *Mermithidae.* The *Steinernematidae* and *Heterorhabditidae* families have been used to manage insect pests primarily (Poinar et al., 1990). By penetrating the target through natural openings like the mouth, anus, and cuticle, nematodes can infect and destroy insect pests. Table 5 below provides a list of frequent nematodal species that are harmful to termites.

Despite several advantages, nematodes as biocontrol offers limited effectiveness, specificity, and slow action. The physical and chemical characteristics of soil (such as moisture, temperature, oxygen, pore size, carbon dioxide levels, pH, salinity, and the presence of artificial chemicals) as well as biotic factors (such as competitive interactions with other soil species, restricted motility, and termite behaviors) all affect how effective nematodes are in biocontrol programs. Additional investigation into nematode ecology and biology, genetic manipulation, and combinations with other control agents is needed to fully realize their insecticidal potential

Table 5. Nematodes species parasitic to termites.

Nematodes	Termites	Mortality	LD_{50}	Country	References
H. bacteriophora	*Microcerotermes diversus*	43.6% after 48 hours	57.9 IJ/ml	Iraq	Zaidawi et al., 2020
Steinernema pakistanense,	*Microtermes obesi*	100% after 48 hours		Pakistan	Javed et al., 2021

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S. Bifurcatum			350 -650 IJ/ml).		
Steinernema carpocapsae, *Heterorhabditis bacteriophora* and *Heterorhabditis indica*	*Odontotermes obesus*	*S. carpocapsae* (58.46%), followed by *H. bacteriophora* (45.45%) and *H. indica* (32.39%) after 48 hours	1000 IJ/ml	Pakistan	Aslam et al., 2023
Heterorhabditis indica	*Odontotermes obesus*	87.98 % after 48 hours	600 IJ/ml	India	Afroz et al., 2023
Steinernema siamkayai, *S. pakistanense* and *Heterorhabditis indica*	*Reticulitermes flavipes and Odontotermis hornei*	80% mortality *S. pakistanense* in 15.5 hrs, *S. siamkayai* in 16.3 hrs *H. indica* in 19.8 hrs	5.84 IJ/ml, 5.68 IJ/ml, 5.00 IJ/ml	Pakistan	Razia and Sivaramakrishnan, 2016
Steinernema karii	*Coptotermes formosanus*	100% mortality after 96 hours	Not Known	Kenya	Wagutu et al., 2017
Steinernema feltiae	*Reticulitermes tibialis*	Not Known	Not Known	USA	Epsky and Capinera,1988
Steinernema thermophilum	*Odontotermes obesus*	42 - 48 % mortality after 72 hours	Not Known	India	Rathour et al., 2014
Heterorhabditis sonorensis Azohoue2	*G. mellonella*	63.2% mortality after 48 hours	Not Known	India	Rahman et al., 2011
Steinernema riobrave Cabanillas	*H. aureus*	80% mortality after 3 days	Not known	USA	Yu et al., 2006

3.3.5. Potential of Viruses as Biocontrol Agent for Termites

Some viruses act as biocontrol agents for termites by infecting and killing them. Until now, very little research has been conducted on virus activity against termites. Among viruses, the *Baculovirid*ae family, which includes granuloviruses and nuclear polyhedrosis viruses, has the highest potential for biocontrol. *Baculoviruses* have been shown to reside in more than 400 insect species, the majority of which are found in the *Lepidoptera* and *Hymenoptera* orders. Gibbs et al., 1970 found a virus that attacked *Coptotermes lacteus* and was related to the virus that causes acute paralysis in honey bees, *Apis mellifera*.

Al Fazairy et al.,1988 discovered that a nuclear polyhedrosis virus isolated from *Spodoptera littoralis Boisduval* was infectious against the *K. flavicollis* (Kalotermitidae). Termites died 2–10 days after infection in the lab, leading scientists to believe that using NPV (Nuclear Polyhedrosis Virus) to control *K. flavicollis* would be possible.

Baculovirus is a useful supplement to broad-spectrum insecticides due to its effectiveness, specificity, and capacity to generate secondary inoculum. They are a crucial component of integrated pest management (IPM) because, unlike other biological control agents, they do not negatively impact beneficial insects. Nevertheless, employing the virus to manage pest populations has many drawbacks. For instance, large production of the virus is challenging due to its demand for a living host or tissue culture. Additionally, they eventually eradicate their hosts.

3.3.6. RNAi for Termite Management

In an effort to shield plants against pest infestations, scientists have recently focused on RNA interference (RNAi) technology. RNAi is a natural biological process that regulates gene expression by inhibiting the translation of particular mRNA molecules. In the context of termite management, researchers have investigated the use of RNAi to target critical genes in termites, potentially affecting their biological processes and eventually controlling their populations (Zhu et al., 2020).

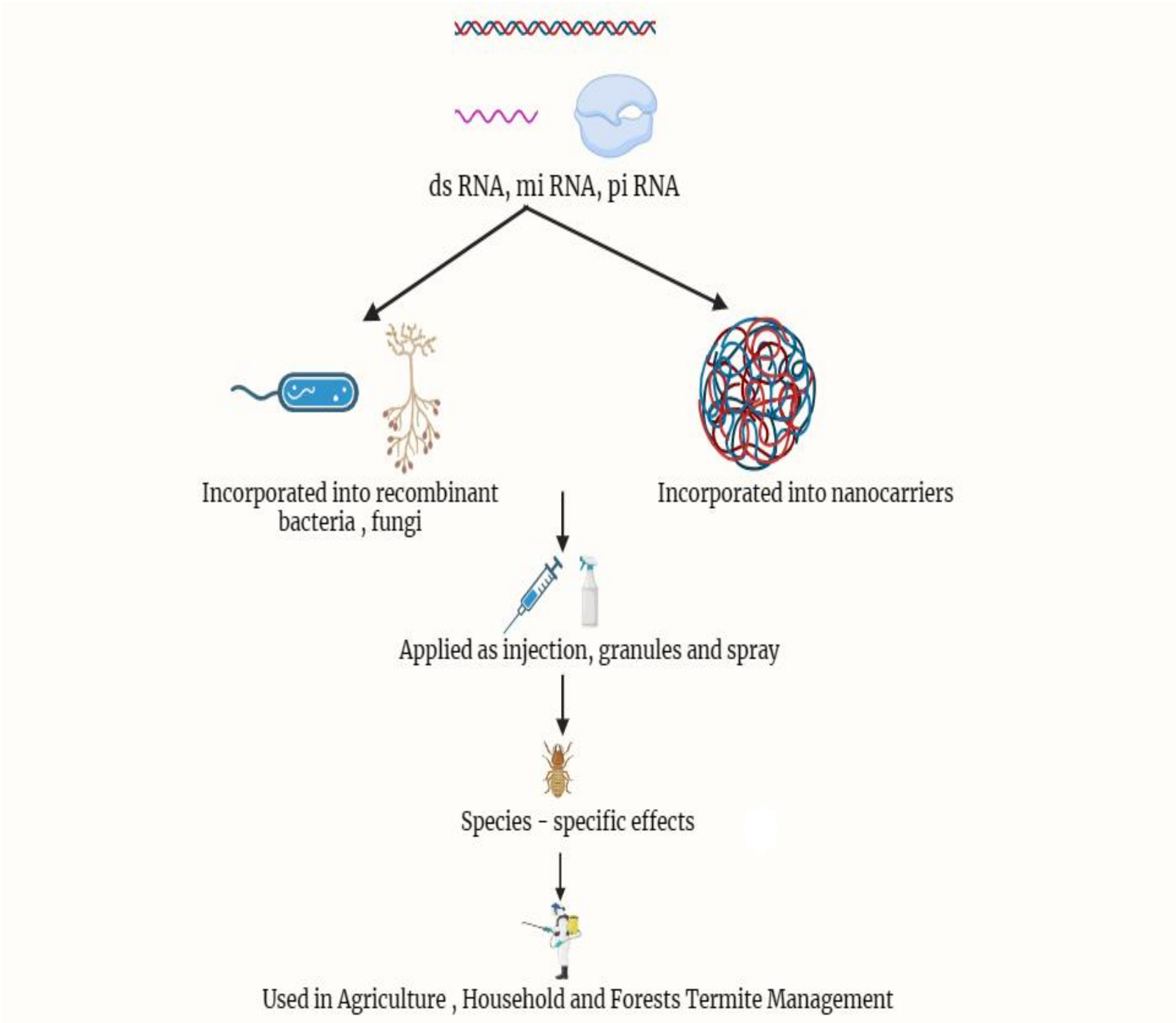

Figure 8. RNA interference against Termites (Source: This study).

The initial study on RNA interference (RNAi) was carried out on *R. flavipes* through the injection of short interfering RNA (siRNA), which produced siRNA against two hexamerin genes (Hex-1 and Hex-2) linked to the regulation of caste polymorphism. Later, two termite genes in *R. flavipes* were targeted by Zhou et al., 2008 using the dsRNA feeding approach. These genes were for the cellulase-digesting enzyme endoglucanase and the caste-regulating hexamerin storage protein hexamerin. The selenoprotein T (SELT) gene's capacity for active immunization against *R. chinensis* termites was investigated by Zhao et al. in 2020. After SELT and TG were knocked down, Zhao et al., 2020 found that both proteins are crucial for producing active immunity against the entomopathogenic fungus *M. anisopliae* in *R. chinensis.*

Termite metabolism may be affected by isotrate dehydrogenase (IDH), and dysregulation of IDH leads to an increase in apoptotic lesions and high infection and mortality rates (Liu et al., 2020). According to Zhao et al., 2020 and Esparza-Mora et al., 2020, GNBP2 and TG also play a role in termite behavioural defence by controlling cannibalistic and grooming behaviours respectively. According to Liu et al., 2022, termites with Dicer-1-mediated miRNA dysregulation expressed fewer genes related to antioxidant defence and glucose metabolism, which significantly reduced the termite's ability to combat fungal growth. Additionally, termites treated with miR-71-5 stimulant showed a reduction in overall antifungal activity, suggesting a detrimental effect of miRNA dysregulation on termite physiological defences.

The main barriers to the broad use of RNAi for termite pest management are its effectiveness, delivery challenges, off-target and non-target effects, immune responses and potential resistance development.

Table 6. RNAi for controlling Termites.

Species	Target gene	Target Gene Function	Type of RNA	Delivery Method	Country	References
Reticulitermes chinensis and *Odontotermes formosanus*	Olfactory coreceptor	Necessary for odorant detection	dsRNA	Injection	China	Gao et al., 2020
Odontotermes formosanus	Termicin	Antifungal activity	dsRNA	Feeding	China	Feng et.al, 2022
C. formosanus	Protistan gene	Important for protists lignocellulosic process	siRNA	Feeding	China	Liu et al., 2017
Zootermopsis nevadensis	Met, 20E signaling and nuclear receptor, Hormone receptor 39	Methoprene Tolerant maintains the action of juvenile hormone 20 E signaling and nuclear receptor regulates egg development Hormone Receptor 39 helps in reproductive gland development	dsRNA	Injection	Japan	Masuoka et al., 2018
			ds RNA	Injection	Japan	Sugime et al., 2019

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Hodotermopsis holmgreen	Dac and Distal less	Dac helps in egg and legs development Distal less involved in egg development				
Nasutitermes takasagoensis	Deformed gene	Involved in determining mandibular positional information during pre-soldier differentiation	siRNA	Injection	Japan	Toga et al., 2013

4. Conclusion

Termites are becoming a more serious menace to the world economy. Many Integrated Termites Management (ITM) components have received a lot of attention, but more focused efforts are still needed. Furthermore, several physical and chemical termite treatment options are available. The widespread use of chemical-based pesticides harm crops and increase the risk of secondary pollution.

Biopesticides have been demonstrated to be the most effective and necessary method of treating termites. Many plant extracts were discovered to be useful against termites, while some botanicals were not as powerful as chemicals. Microorganisms such as fungus, nematodes, bacteria, and viruses are effective termiticides. They kill termites effectively by creating siderophore, poisons, lytic enzymes such as protease, chitinase, and secondary metabolites like HCN. Nowadays, indoor termiticides based on RNAi are probably used to protect wooden structures. In conclusion safer, eco-friendly and cost- effective mode of strategy to reduce the termites can be practised using microorganism, plants extracts and RNA interference for restoring the biological and physiochemical composition of our ecosystems.

However, there are some issues with the use of microorganisms, such as the fact that they become inactive under certain extreme environments. Furthermore, these microbial entities have some leaching issues, which have become a source of contamination of ground water and have caused various water-borne diseases. Long-term pest management control cannot usually be achieved by a single microbial control agent. As part of a comprehensive plan in all farming methods, entomopathogens and their enzymes could offer cost effective, safer, substantial and targeted pest control without compromising the efficacy of other methods.

5. Future Prospectives

The efficacy and sustainability of integrated control strategies should be enhanced in the near future by the synergistic pairing of microbial control agents with other technologies. Technologies including improved biological control agents, precise targeting, and genetically modified organisms (GMOs) may provide environmentally acceptable and long-lasting pest management solutions. The majority of investigations on checking biocontrol efficacy are conducted at the research level or on a lab scale; further studies are required to determine the effectiveness of these methods in real-world settings. More research is also needed to assure the long-term release and efficacy of microbial application methods used as biocontrol. Many of the difficulties that microbial control is currently facing should be resolved by advances in microbial products and increased public understanding regarding the advantages of biological control through government support, media outreach, and educational programs.

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Abbreviations

BCA, Biological Control Agents; USD, United States Dollar; RNAi, RNA Interference; CCO, Cytochrome C Oxidase Enzyme; HCN, Hydrogen Cyanide; IJ, Intra jugular; siRNA, Short Interfering RNA; dsRNA Double stranded RNA; Hex, Hexamerin; IDH, Isotrate Dehydrogenase; SELT, Selenoprotein T; NPV, Nuclear Polyhedrovirus; IPM, Integrated Pest Management; GMOs, Genetically Modified Organisms; ITM, Integrated Termites Management

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