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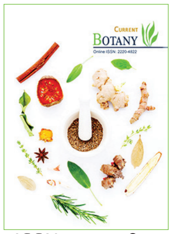

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Biological approaches of termite management: A review

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ABSTRACT

For increased crop production, the role of chemical termititoxicant cannot be neglected as they have provided the efficient way to achieve green revolution. But the present scenario has forced mankind to search for alternative options. While keeping in mind the concept of sustainable agriculture, pest management including termites and other phyto-diseases etc. needs to be focused. For the achievement of the above stated goal, eco-friendly and cost-effective strategies need to be emphasized. Biopesticidal agents that mainly comprise of herbal and microbial formulations are known to exhibit anti termite activity and have a pivotal role in the production of organic food products. In order to reduce the chemical consumption, the vast area of biological alternatives needs to be explored as they provide us with many beneficial aspects like sustainability, suitable application, biodegradable nature, target specificity etc. Further, the bioactive components of such biological agents can later be used as commercially viable termititoxicant in the form of formulations. These herbal and microbial termititoxicants are effective and have immense scope to be used in future for sustainable development.

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INTRODUCTION

Termites are a major threat to wooden infrastructure and agricultural crops in tropical areas. Termites are generally classified on the basis of their habits and habitats into wood inhabitant and ground inhabitant. Wood occupants consist of species that share humid forest and dry wood. The ground-occupants are graded into mound-builders, subterranean and carton-nest builders (Pearce, 1997). Termites have a broad range of feeding habits that includes faeces, deceased or rotten plant material and soil with organic constituents (Freymann *et al.*, 2008). The termites undergo burrowing activities like modification of edaphic composition and structure (Lee and Wood, 1971), recovery of drainage and soil aeration (Donovan *et al.*, 2001) thereby altering the soil profile. The cryptocercidae roaches of late Jurassic of Mesozoic Era could be credited for the origin of termites (Engel *et al.*, 2009). Termites possess highly ordered colonies characterized by overlapping generations belonging to similar descendants with *Periplaneta americana* Linnaeus (Inward *et al.*, 2007). The Isoptera order is classified into seven families Mastotermitidae, Kalotermitidae, Hodotermitidae, Termopsidae, Rhinotermitidae, Serritermitidae, Termitidae. Family termitidae accounted as higher termites, whereas lower termites are known in case of families Termopsidae, Kalotermitidae, Mastotermitidae, Hodotermitidae, Rhinotermitidae and Serritermitidae. Termitidae family members are eurytopic, have a broad range of social specifications and wide-ranging distribution with the utmost multiplicity recorded in tropical forests (Kambhampati and Eggleton, 2000). Four families are distributed among the most destructive organisms, viz., Rhinotermitidae, Kalotermitidae, Hodotermitidae and Termitidae (UNEP Report, 2000).

Out of 300 termite species reported from India; about 35 caused damage to crops and buildings. In India, the major mound-building species are *Odontotermes obesus* (Rambur), *Odontotermes redemanni* (Wasmann) and *Odontotermes wallonensis* (Wasmann), and the subterranean species are *Heterotermes indicola* (Wasmann), *Coptotermes ceylonicus* Holmgren, *Coptotermes heimi* (Wasmann), *Odontotermes horni* (Wasmann), *Trinervitermes biformis* (Wasmann), *Microtermes obesi* Holmgren and *Microcerotermes beesoni* Snyder (Rajagopal, 2002). They cause much economic losses throughout the world (Fig. 1). The agricultural sector pays heavily for the losses accredited to termites which encompass approximately several millions of rupees. In India, different regions have evidenced the severe losses caused by termites like southern part crops such as maize, groundnuts, sunflower and sugarcane and northern India includes wheat and sugarcane, north eastern side has tea whereas western India comprises cotton.

While chemical pesticides are of major importance to manage termites but their harmful side effects and their consistent application gave rise to degradation of the environment. This led to the environmental concerns, which exhorted researchers to be on the lookout for plant derived compounds to serve either as an alternative or zero toxicity or permissible toxicity level for human health. Plants are rich sources of bioactive compounds and around 2000 plants of 60 families having insecticidal property can therefore be used as a potent remedy for insect-control (Dev and Koul, 1997). Instead of chemical pesticides, plants could provide a better substitute because of their constituents having different bioactivities such as repellents, insecticides, arrestants, antifeedants, (IGRs) insect growth regulators etc. (Kannaiyan, 1999).

CONSEQUENCES OF CHEMICAL PESTICIDES

Extensive use of chemical pesticides, their accumulation in the atmosphere and reckless disposal of chemical waste causes ecological instability and a significant threat to our well-being. The awareness of the adverse effects has driven researchers to look for greener alternatives in the world. Numerous termititoxicants containing active ingredients (bifenthrin, chlorfenapyr, cypermethrin, fipronil, imidacloprid, and perméthrin) are licensed under various brand names around the world. In tropical areas, aldrin, dieldrin, chlordane, heptachlor, and HCH are common. In India, the termites are managed using chlorpyriphos, lindane, imidacloprid, chlorfenapyr.

To control infestation of drywood termites, chemical fumigation is employed. The active ingredients in various fumigants are carbon dioxide, methyl bromide phosphine and sulfuryl fluoride.

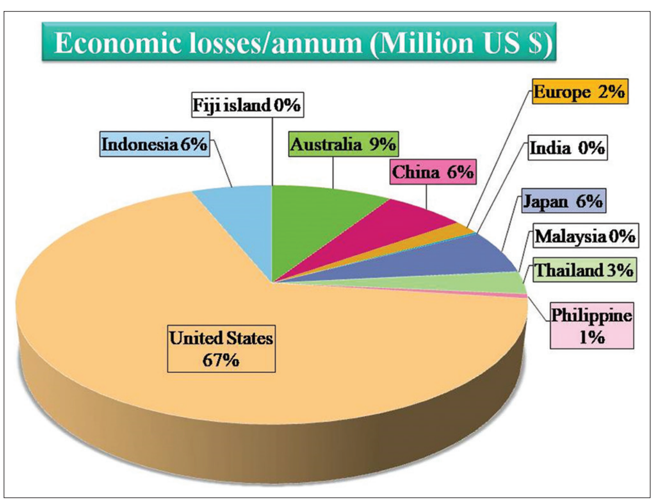

Figure 1: Worldwide annual economic losses due to termites (Ahmad, 2019)

Methyl bromide is a popularly used fumigant that enters quickly and deeply into materials under normal atmospheric pressure and is toxic on the insect nervous system. Methyl bromide is a chemical which depletes ozone. It breaks down to form bromine which takes part in a series of chemical reactions that depletes ozone. Ozone depletion remains a major global ecological problem. According to Montreal Protocol on Substances Depleting the Ozone Layer and the Clean Air Act (CAA), the amount of methyl bromide manufactured and imported into the United States has been decreased incrementally until it has been phased out. In September 1997, 160 countries amended and ratified the Montreal Protocol.

Although chemical pesticides were used as restorative measure to overcome the losses caused by insects and pest, their rampant use resulted in lethal consequences globally causing human health hazard; reduction in soil fertility and damage; low productivity of land converting into the barren land, air, soil and water pollution; biodiversity loss besides affecting non-target organisms and even entered and persisted in the food chain due to their non-degradable nature (Fig.2). In India, the first pesticide poisoning case was reported in Kerala (1958) where wheat flour contamination by Parathion had killed around 100 people after consumption (Karunakaran, 1958).

Since then regular reports are being registered for chemical toxicity till now. Inappropriate doses and usage without the knowledge of constituents of these chemical pesticides led to resistance in the insects and pests. Variety of pesticides, applied to crops and plants, ultimately enter into humans and animals through food and drinking water, which bring up various modern diseases like cancer, parkinson, paralysis, abnormal infants, increasing pregnancy risks etc. At the global level, approximately one million/year deaths and chronic disorders are attributable to pesticide poisoning (Environews Forum, 1999).

DIVERSITY OF BIOPESTICIDES AND ITS ACTIVITY AGAINST TERMITES

For the protection of crops, a new area of interest emerged in the field of biopesticides as we become alert about the human health disorders and other related side effects on the ecosystem that are resulted from the persistent use of chemicals pesticides (Nas, 2004). Biopesticides comprising of bacteria, viruses, fungi, nematodes, animals and plants are more advantageous than chemical pesticides because of their target specificity and least detrimental effects. Chemical based fertilizer besides killing the termites also adversely kills the other non-harmful insects, several birds and mammals. Biopesticides are biodegradable in nature (Devlin and Zettel, 1999) and have a supplemental role with chemical pesticides which makes them an efficient alternative to be used in the field of insect pest management and organic agriculture (Fig.3).

Current Status of Biopesticides

Over the globe, application of biopesticides has increased drastically because of the rise in demand for good quality food

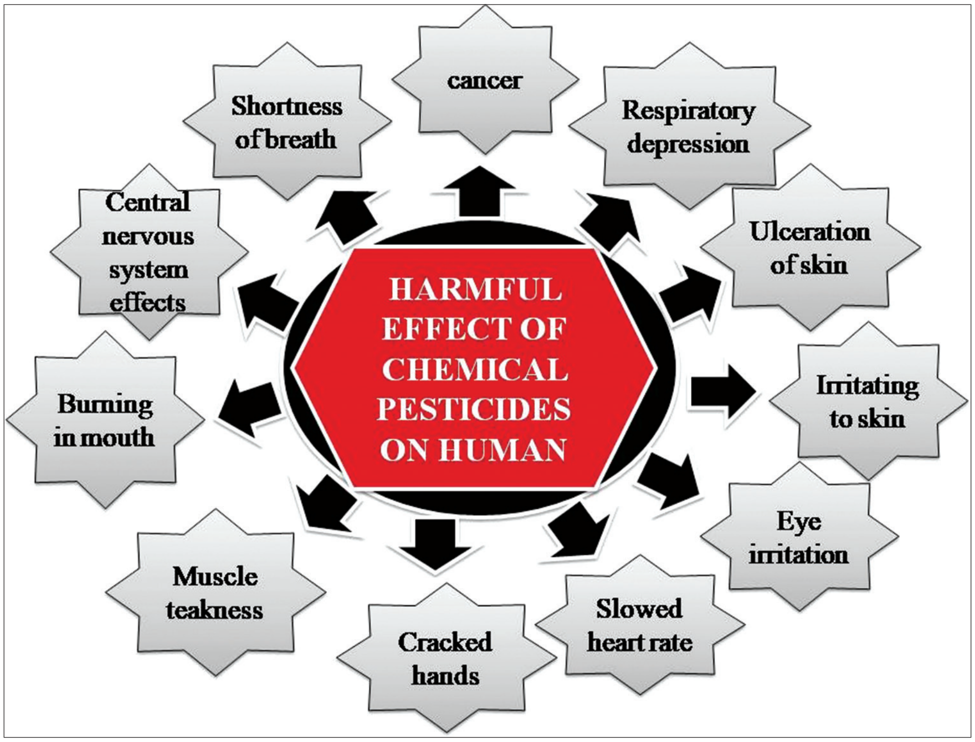

Figure 2: Effect of chemical pesticides on humans

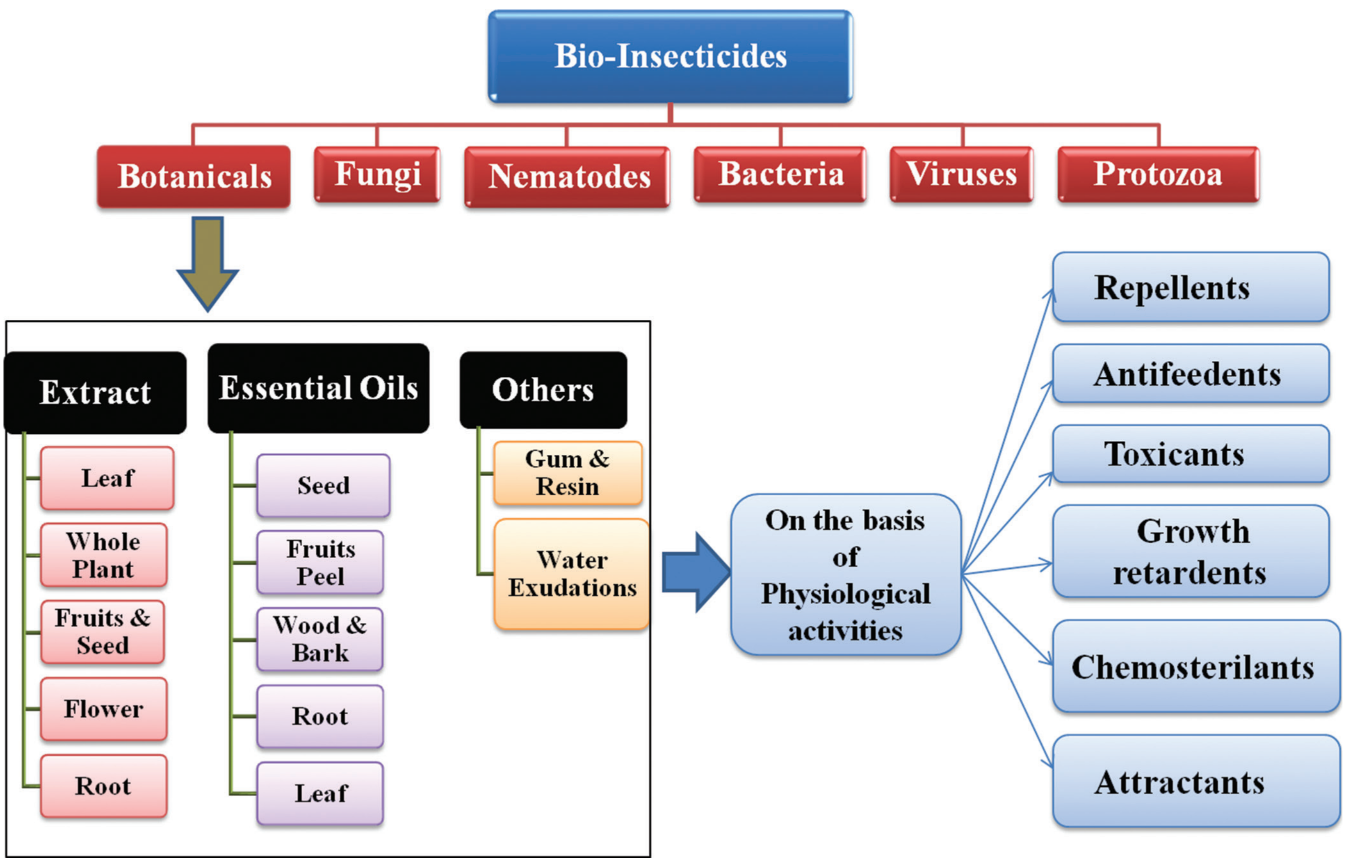

Figure 3: Diversity of different biopesticides and its physiological activities against termite

of organic nature. Consumption of biopesticides increased drastically in India during the past decade. In India, the production of biopesticides accounts for 3% whereas globally it is around 4.5% of the total chemical pesticides production.

Biopesticides including *Bacillus thuringiensis* (*Bt*) and *Azadirachta indica* (Neem) are the most frequently used ones.

India possesses wealthy biodiversity having a number of plants exhibiting biopesticidal potential but there is a gap in biopesticides research and formulation. Thus, to overcome this situation consistent efforts are needed in this area of research which would ultimately result in commercial biopesticides production.

Botanicals Pesticides

Various plants and its parts showed termititoxicant properties including termiticidal, antifeedant and insect growth regulation. Many plants and their parts *viz*., essential oil, seed, bark, leaf, fruit, root, wood and resin reported to possess anti-termite properties (Verma *et al*., 2009). Many essential oils for instance *Vetiver* oil having long term activity has been assessed for its repellant and toxic effect against termites (Zhu *et al*., 2001a and 2001b). The toxic effect shown showed by Vetiver oil from root on formosan subterranean termites was mainly due to a sesquiterpenoid component- nootkatone, accountable for the strong repellent and anti feeding activity (Maistrello *et al*., 2001; Zhu *et al*., 2001b). When compared to *Chrysopogon* zizanioides oil, Nootkatone was found to be more lasting and it produces undesirable effects for one year on termites (Maistrello *et al*., 2003). Anti termitic effect of active constitutent- Nootkatone as compared to the essential oil from roots of *Chrysopogon zizanioides* was found to be more lasting i.e. persisted for one year (Maistrello *et al*., 2003).

For controlling formosan subterranean termites, a new biopesticides combination comprising of *C. zizanioides* oil and nootkatone can be used as a potting material with soil, wood, and mulch (Mao and Henderson, 2007). In case of formosan subterranean termites, an application of vetiver grass root mulch treatment has resulted in reduced tunneling activity and enhanced death rate. The potent insecticidal agents including sesquiterpenoids can be supplemented by the modified vetiver oil (Chauhan and Raina, 2006).

Application of Botanical Extracts as Termititoxicants

Bioactive components from different plant parts can be extracted to use them in the management of termites (Table 1). The extracts can target the Formosan subterranean termites hindgut and by destroying the microbes (Doolittle *et al*., 2007), thereby play the role of antifeedants and deterrents (Ohmura *et al*., 2000; Boue and Raina, 2003). The anti termite activities have been reported in extracts of hexane, methanolic and various solvents of different plants like Juniperus species and of tarbush *Flourensia cernua* (Adams *et al*., 1988)

Bithiophene and terthiophene among the eight isolated thiophenes exhibited complete mortality in termites. The natural defense system in certain plants provided them coverage against termites due to the presence of bioactive components present in them (Onuorah, 2000; Verma *et al*., 2009). Isolation from *Catalpa bignonioides* has resulted in four compounds namely, epicatalponol, catalone, catapalactone and decatalponol out of which the epicatalponol and, catapalactone exhibited potent termititoxic activity against the test termite

Table 1: Termititoxic effect of some botanicals.

S. No.	Plant name	Plant part	Active compound	Termite (s)	Effect	Reference (s)
1.	Murraya koenigii (L.)	Leaf	Flavonoid	C. gestroi	Toxic	Muda *et al.,* 2018
2.	*Phyllanthus niruri* (L.)	Leaf	Tannins	*G. sulphureus* and *C. gestroi.*	Toxic	Bakaruddin *et al.,* 2018.
3.	*Withania somnifera* (L.), *Croton tiglium* (L.)	Seed	Triterpenoid, 2, 2 beta acetoxylantic acid	O. obesus	Toxic	Ahmed *et al.,* 2007.
4.	*Andrographis paniculata* (Burm.f.)	Leaf	Flavonoids	*G. sulphureus* and *C. gestroi*	Antifeeding	Bakaruddin *et al.,* 2018.
5.	*Leucaena leucocephala* (Lam.)	Leaf	Squalene, phytol	*C. gestroi*	Toxic	Bakaruddin *et al.,* 2018.
6	*Rollinia mucosa* (Jacq.)	Seed	Terpinoid	*C. gestroi wasmann*	Repellent and antifeeding	Acda MN, (2014).
7.	*Capparis deciduas* (Forssk.)	Stem	Thiophenes, alkaloid	*O. obesus*	Toxic	Upadhyay *et al.,* 2010.
8.	*Lantana camara var. aculeate* (L.)	Leaf	Triterpenoid,22 acetoxylantic acid	*O.obesus*	Toxic	Verma *et al.,*2006.
9.	*Ocimum bacilicum* (L.)	whole plant	Alkaloid, matrine and oxymatrine	*Heterotermes indicola (Wasmann)*	Antifeedant and repellent	Rasib *et al.,* 2017
10.	*Jatropha curcas* (L.)	Seed	Cardanol, methyl anacardate.	*Microcerotermes beesoni*	Toxic	Singh *et al.,* 2008
11.	*Achyranthes aspera* (L.)	leaf	Flavonoids	*O. obesus*	Toxic	Patel *et al.,* 2017.
12.	*Sextonia rubra* (Mez.)	Wood	Rubrynolide	*R. flavicepes*	Toxic	Tasciogluet *al.,* 2012
13.	*Syzygium cumini* (L.)	Leaf	Saponins	*O. obesus*	Toxic	Patel *et al.,* 2017.
14.	*Solanum surattense (Burm. F.)*	Latex	Quinones	*O. obesus*	Mortality	Sahay*et al.,* 2014
15.	*Argemone mexicana L.,*	Leaf	Chlordane	*O. obesus*	Mortality	Nagare and Pardeshi, 2019.
16.	*Aristolochia bracteata (Retz.)*	Leaf	Quinines	*Odontotermes obesus Rambur*	Mortality	Sahay *et al.,* 2014
17.	*Calotropis procera* (Aiton.)	Leaf	Alkaloids, saponins	*O. obesus*	Toxic	Sahay*et al.,* 2014
18.	*Callistimon viminalis* (Gaertn.)	Leaf	2-methyloctane, undecane. Terpenoid, flavonoid.	*O. obesus*	Antifeedant	Zubair *et al.,* 2013.
19.	*Allium sativum* (L.)	Leaf	*Tannin, saponin*	*M. bellicosus*	Toxic	Osipitan *et al.,* 2013
20.	*Citrus (Peel)*	Peel xtract	d-limonene	*C. formosanus*	Mortality	Raina *et al.,* 2007
21.	*Pongamia pinnata* (L.)	Seed	Karanjin, phorbol esters	*O. obesus*	Toxic	Verma *et al.,* 2011

Reticulitermes flavipes (Fang and Casida, 1999). In order to provide protection from insect's attack resins procured from plants have played a significant role (Birkett *et al.*, 2008).

Application of Essential Oils as Termititoxicants

The essential oils from different plant parts are known to show termiticidal properties. Essential oil of *Tagetes erecta* leaf has termiticidal activity due to presence of (Z)- ocimene (42.2%). Aerial parts of *Lepidium meyenii* Walp. contains essential oil which acts as a feeding deterrent to termites. Similarly, essential oil obtained from aerial part of *Nepeta cataria* L. function as an obstacle against termites (Peterson and Ems-Wilson, 2003). Essential oils from coniferous species, *Calocedrus macrolepis* and *Cryptomeria japonica* (heartwood and sapwood) and *Chamaecyparis obtusa* (leaf) showed significant anti-termitic action against *C. formosanus* (*shiraki*), complete mortality was attained after five days of test at 10mg/g dose. *Calocedrus macrolepis* var. *formosana* heartwood essential oil exhibited highest termiticidal property with LC-50 value of 2.6 mg/g (Cheng *et al.*, 2007). The oil of *Melaleuca cajuputi* when compared with that of *M. gelam*, the latter turned out to be more active (Sakasegawa *et al.*, 2003).

Application of Resin as Termititoxicants

Several trees like Dipterocarp *spp.* known for its immune response from pests. It was reported that *Shorea robusta* showed high resistivity against termites. It was found that the items that are manufactured by the use of Sal wood showed resistance against termites. Resistivity properties of Dipterocarp woods cause momentous increase in death rates of termites (Mishra *et al.*, 2020).

Classification of Termititoxicants:

Based on physiological activity of insect, Jacobson (1982) has conventionally classified the components of the plants into 6 groups, i.e.(i) Repellents, (ii) Feeding deterrents/antifeedants, (iii) Toxicants, (iv) Growth retardants, (v) Chemosterilants and (vi) Attractants/Stimulators.

- **(i) Repellents:** Since decades plant-based repellents have been used, as it provides safeguard with negligible effect on the environment. Due to their non-toxicity to environment, they push the bug-pest away from the products being handled by activating olfactory as well as other receptors in plants. Plants repellents are effective in pest management and can reduce the usage of conventional pesticides; ensure the health of humans, animals and the environment. Different parts of plants (extracts, powders and essential oil) are described as repellent for termites. For example, *P. niruri* methanolic extract has been found to be an excellent termititoxic activity because of its high repellent activity against *G. sulphureus* and *C. gestroi* exposure for 72 hours. (Bakaruddin *et al.*, 2018).
- **(ii) Feeding deterrents/antifeedants:** Chemicals that inhibit feeding or disturb insect feeding by making the materials unattractive or unpleasant are defined as antifeedants, and sometimes referred to as "food deterrents". Many naturally occurring antifeedants include steroidal alkaloid glycosides, aromatic steroids, hydroxylated steroid meliantriol, hemiacetal triterpene and others. *Ocimum canum* possessed significant feeding deterrence or antifeedant against *Macrotermes* sp. (Owusu *et al.*, 2008).
- **(iii) Toxicants:** In the last few years,research on new plant-derived toxicants has augmented. Worldwide reports on plant derivatives showed that many plant products exhibited toxicity against termites. For example, essential oils of *Mentha arvensis*, *Cymbopogon citratus* and *Carum capticum* were found to be exhibit an excellent termiticidal activity because of its strong toxic action against *O. obesus*. Leaf extract of *Lantana camara var. aculeate* showed toxic activity against *O. obesus* (Verma *et al.*, 2005).
- **(iv) Growth retardant:** Some plant extracts have deleterious effects on insect growth and development and significantly reduced pupal and adult larval weight, extended larval and pupal cycles and decreased pupal recovery and adult outbreaks. Experimentally it was found that changes actually happened in the body of the termites after treating with different formulations of extracts and the most affected part of termite's body was abdomen which shrunk in treated ones in comparison to control (Rajashekar *et al.*, 2012).
- **(v) Chemosterilants (Reproduction inhibitors):** Plant parts are used to reduce insect ovipositor, egg hatchability, post-embryonic development and progeny production according to various research reports. Rajashekar *et al.*, 2012 reported mortality of insect eggs by using plant extract caused.
- **(vi) Attractant/Stimulators:** Botanical termititoxicants have long been regarded as potent supplements for chemical termiticides in pest management due to their eco-friendly and minimal toxicity to humans. The products obtained from plants are non-phytotoxic, systemic and biodegradable and thus are important in the management of pests (Mishra and Dubey, 1994).

CHEMICAL STRUCTURE AND TERMITITOXIC ACTIVITY OF ACTIVE COMPOUNDS OF PLANTS

A relation might exist among the chemical structure of botanical and its termititoxic activities (Scheffrahn and Su, 1987). Non halogenated acids cause a minor effect on mortality of *C. formosanus*. A comparison was done with wood consumption by termites with 2-brominated acid, it was found to be more lethal as termites feed less. Haloacid methyl esters had an inconstant effect on anti termite activity which might be related to the distance end to end of the carbon chain. Treatments of ester and 2-Iodo Octadecanoic acid were highly lethal and low consumption was observed than 2-bromo compounds, therefore high activity was seen as compared to their 2-chloro analogs. Methyl, ethyl, and isopropyl-2-halooctadecanoates were similar or more toxic than their specific halo acids. Slow-acting insect-toxicants used in termite baits are noviflumuron ($C_{14}H_9ClF_9N_2O_3$), bistrifluron ($C_{16}H_7ClF_8N_2O_2$), hexaflumuron ($C_{16}H_8Cl_2F_6N_2O_3$), and diflubenzuron (Crompton-Dimilin $C_{17}H_7Cl_2F_2N_2O_3$). Noviflumuron is stronger and has quicker activity. Karr *et al*.,(2004) and King *et al*.,(2005) found that Noviflumuron is responsible for the higher mortality in *R. speratus* compared with diflubenzuron and haxaflumuron. Kubota *et al*., (2006) reported that Bistrifluron demonstrates a speedier action rate against *C. formosanus* than hexaflumuron. Su and Scheffrahn,(1993) observed that hexaflumuron is a bait toxicant against both *Reticulitermes flavipes* and *Coptotermes formosanus*. The anti-termite activity of these toxicants is increasing because their chemical structure also increases the number of fluorine molecules. (Ohara *et al*., 1991) reported that saponins isolated from *Pometia pinnata*, with a single sugar chain had more termititoxic efficacy as compared to two sugar chains.

Termititoxic activity also depends on the length of the sugar chains, long chain have weaker activity. Methyl oleanolate-3-yl β-D-glucoside and methyl oleanolate-3-yl β-D cellobioside demonstrated maximum antifeedant activity against *Reticulitermes speratus* and decreased activity as a result of the expansion of the sugar chain unit (Ohmura *et al*., 1997). The hydrophilic nature of molecules enhance with increasing quantities of sugar residues, it is predicted that sufficient polar behaviour is required to expose triterpenoid saponin's termititoxic activities. These studies indicate that the factors that influence the termititoxic activity are the number of sugar chains, halogenation and length of carbon-chain present in the active component (Ohmura *et al*., 1997).

APPLICATION OF MICROBIAL BIOPESTICIDES

Microbial biopesticides originated from bacteria, fungi, algae, viruses or protozoans that exist naturally or are genetically transformed. They kill pests either by creating a toxin that is specific to the insect and by generating disease (Clemson, 2007). Microbial biopesticides are transmitted to the cropsas live, dead and in spore form. The most widely used microbial pesticides are *Bacillus thuringiensis* (Bt) strains, which constitute approximately 90 per cent of the demand for biopesticides (Chattopadhyay *et al*., 2004). Baculo-viruses are the pathogens which attack insects and other arthropods in general. Unlike other members of this group, they are not considered living organisms but rather reproduce microscopic elements in a parasitic manner (US e-CFR, 2008). Baculoviruses are extremely small and are mainly composed of double-stranded DNA that is essential for the virus to develop and replicate itself. As this genetic material is quickly damaged by interaction with the sunlight or by conditions in the gut of the host, a protein coat called a polyhedron covers an infectious baculovirus particle (D'Amico, 2007). Fungal biopesticides are used to control insects, plant diseases with other fungi or bacteria, nematodes and weeds. They are also parasitic or develop bioactive metabolites such as enzymes that penetrate the walls of plant cells. Several researchers from all over the globe are focusing on pest and disease control agents for biocontrol (Tapwal *et al*., 2005). A*spergillus flavus* (fungus), the strain AF36 of which is used as a cotton fungicide. Some A. *flavus* strains contain a highly toxic compound known as aflatoxin in cotton seeds, which is carcinogenic to the liver. AF36 strain of A. *flavus* does not contain aflatoxin. Thus, applying the AF36 strain to cotton fields reduces the amount of aflatoxin producing fungus that would then be developed to protect workers and the public (US EPA Fact Sheets, 2008).

Termite-associated Microbial Chemical Interaction

Subterranean termite nest contain carton material which is a specific niche and the fecal material acts as nutrition for the growth of actinobacteria and multiple shapes of microbes which offer chemical defenses against additional microbes. The colony of termites benefits greatly with the broad range of actinobacterial strains found in the carton to avoid pathogenic soil fungi infections. *Metarhizium anisopliae* (Basionym) fungal infection on termites was significantly decreased by the use of biologically active actinobacteria (Chouvenc *et al*., 2013b). Microbes present in the carton material are in continuous competition for inadequate nutrients with each other, and this ongoing competition triggers a chemical reaction among the microbes. The chemical interactions released some molecules which function in chemical defense and nutrient gain signaling. The actinobacteria associated with termites have great selection pressure for the production of efficient and novel groups of biologically active small molecules (Carr *et al*., 2012; Kang *et al*., 2016). Research is focused on microbes associated with insects having symbiotic bacteria which release toxic metabolites which are inhibitory against pathogenic fungi.

Application of Fungi as Termititoxicants:

Fungi are utilized for the management of insects globally (Glare and Milner, 1991). Milner (2000) has reported approximately 700 species of fungal insect pathogens. A fungus penetrates inside the host cuticle to infect, as contamination does not occur by ingestion of the spores or conidia (Milner *et al*., 1998). Pathogenic fungi obtained from termite galleries made of wood and mud which attacked *B. bassiana*, *M. anisopliae* and *Paecilomyces fumosoroseus* (Wright, 2005). *Metarhizium anisopliae* is mostly used against termites for field testing.

Lack of Application of Fungi in Termite Control

Termites have high sensitivity for light, humid environment and temperature. They have a lack of vision but their olfactory sense is highly developed. Termites easily detect conidia from virulent *M. anisopliae* strains and trigger alarm and aggregate around individuals with spore-dust (Staples and Milner, 2000; Myles, 2002). Rosengaus et al. (1998) and Rosengaus and Traniello (2001) researched the behavioral defense mechanism and investigated that allogrooming between termites makes the treatment of fungal spore/conidia ineffective. They also detected that social grooming would remove all the fungal spores/conidia from the treated termites in large colonies. Milner (2003) observed less repellency in termites with less virulent *M. anisopliae* strains.

Rath and Tidbury (1996) found that when *M. anisopliae* was formulated with attapulgite mud and surfactants, conidia became repellent and it could not be noticed by the termite.

Milner (2003) tested five fungal pathogens (*Beauveria bassiana*, *Metarhizium flavoviride*, *M.anisopliae*, *Paecilomyces lilacinus* and *P. fumosoroseus*) against O*dontotermes obesus*, results showed that the termites were prone to infection with all fungi (Khan *et al.*, 1993; Chouvenc *et al.*, 2009). It was found that excessive exposure to fungal infections of A*spergillus* sp. (Pandey *et al.*, 2013) and *Isaria fumosorosea* (Wright and Lax, 2013), worker termites were more susceptible rather than others. These two fungi have been found to cause maximum worker mortality in termite colonies.

Coghlan (2004) developed a strategy for carrying mycelium in termite nests in a pre-sporophytic phase. The termites must bring and inject the fungus into their gardens, where it sporulates and induces mycosis. This approach will only work and become successful, if the termites move the mycelia into their fungal garden and deposit it, rather eating it. Bait bioformulations for the management of termites containing *Metarhizium* conidia were made by (Milner, 2003). In bait, termitesconsume the spores and pass them out in their faeces. The spores covered with faecal matter were viable, but due to antifungal properties of termite feces they could not germinate (Rosengaus *et al.*, 1998). Infection is caused only when fungal spores migrate out of the matrix and get stuck to the body of the termite. The infected termites move through the colony and without any restrictions thereby cause inoculation in small quantities. They would be gathered by healthy workers and covered with fecal matter, hence dropping the probability of disease spreading.

Rosengaus *et al.*, (1999) investigated resistance development in several phyto-pathogens of *Zootermopsis angusticollis*. Commercial preparation of *M. anisopliae*, Bio-Blast™ managed *Reticulitermes flavipes* quite effectively (92%) (Quarles, 1999). Maniania et al. (2002) is a study in Kenya where maize crop was controlled by termite by applying *M. anisopliae* at the sprout stage.

Application of Nematode as Termititoxicants:

The nematodes (phylum Nematoda) are abundant roundworms found in almost every ecosystem across the globe. They are an effective tool in controlling insect populations in ecofriendly way. They are parasitic to insects belong to orders Hemiptera, Diptera, Hymenoptera, Lepidoptera, Orthoptera, Coleoptera, Thysanoptera, Siphonaptera, and Isoptera (Nickle and Welch, 1984). Nematodes families, Mermithidae, Allantonematidae, Steinernematidae, and Heterorhabditidae are very promising in insect management programmes (Popiel and Hominick, 1992).

The termitic-pathogenic nematodes have many features suitable for biocontrol and commercial application as biotermititoxicants as they have: (i) wide range of host soil- species; (ii) effortlessness of manufacture, storage and appliance; (iii) verysafe for vertebrates, plants and non-target organisms;(iv) consent to genetic assortment (Kaya and Gaugler, 1993).

Some studies revealed that the nematodes have the capability to resist against termites. (Merrill and Ford, 1916) revealed that, in field samples, 77 percent of colonies and up to 100 percent of individuals were parasitized by *Mikoletzkya aerivora* of *Reticulitermes lucifugus* (Rossi) (Rhinotermitidae). Laboratory exposure of termites with nematodes resulted in successful contamination (47 percent at 4 days) and a death rate of 100 percent of infected termites in 12 days. Fujii,(1975) observed a death rate of 96 percent in C. *formosanus* in laboratory experiments within 7 days of treatment with *Steinernema carpocapsae* in the infective stage. (Georgis *et al.*, 1982) reported mortality approaching 95 per cent for both Z*ootermopsis* sp. and *Reticulitermes* sp. Within 3 days of laboratory exposure to *Steinernema carpocapsae*, termites carried the infection back to their nests.

Danthanarayana and Vitarana, (1987) demonstrated in tea plants that termites were removed within 2–3 months by first application of nematodes (*Heterorhabditis* sp.; 4,000–8,000 ml of suspension). Evidence suggests that nematode populations in the area were self-perpetuating even in harsh environmental conditions. Epsky and Capinera,(1988) reported that the *Reticulitermes tibialis* subterranean termite was capable of escaping contact with *Steinernema feltiae* nematodes and exploiting coverage holes in nematode-inoculated bait attack areas.

Entomopathogenic nematodes like *Steinernema riobrave*, *S. carpocapsae*, *S. feltiae*, *Cabanillas*sp., *Poinar* sp., *Raulston*sp. and *Heterorhabditis bacteriophora* have potential to infect and kill *Heterotermes aureus*, *Gnathamitermes perplexus* and *Reticulitermes flavipes* in laboratory sand experiments (Yu *et al.*,2006). Mortality of workers of *H. aureus* and *S. riobrave* depends significantly on the concentration of nematodes and the time of incubation as infection rate is highest in sand.

Various factors influence the efficacy of nematodes in biocontrol programmes. These factors are physical and chemical properties of soil (e.g., moisture, temperature, pore size, oxygen and carbon dioxide levels, pH, salinity, and the presence of artificial chemicals) and biotic factors such as competition or competitive interactions with other soil species, restricted motility, and termite behaviors (Gaugler, 1988). Further deep knowledge on genetic manipulation, combinations with other control agents, ecology and biology of nematodes is required for their insecticidal potency.

Application of Bacteria as Termititoxicants:

Few bacteria were tested against termite and exhibited potent anti termite activity (Toumanoff, 1959;Smythe and Coppel, 1965). However, these bacteria have not earned serious consideration for field applications related to termite control. Khan *et al.*,(1977) isolated a strain of *Bacillus thuringiensis* from the termite *Bifiditermes beesoni*. The colony's dry, humid climate speeds the effectiveness of bacterial pathogens (Grace, 1994). Fifteen species of bacteria were used for regulation of C*optotermes formosanus*, with *Serratia marcescens* that caused host mortality at 100% (Osbrink *et al.*, 2001). (Devi and Kothamasi, 2009) reported that the bacteria have been shown to cause termite mortality by inhibiting their respiration. *P. fluorescens* blocked the respiratory system of termite by secreting hydrogen cyanide when tested against termites. (Singha *et al*., 2010) *in vivo* conditions found that the bacterial strains such as *B. thuringiensis* are pathogenic in nature. When tested against *M. beesoni* causes higher lethality at minimal doses.

Application of Viruses as Termititoxicants:

Viruses are also considered as a microbial insect controller (Payne, 1982). More than 400 species of insects of Lepidoptera and Hymenoptera are hosts of baculoviruses. Very less work was done till now on virus activity against termites. Gibbs *et al*.,(1970) isolated a virus that infects *Coptotermes lacteus*, similar to the honey bee paralysis virus A*pis mellifera* L. A nuclear polyhedrosis virus, obtained from *Spodoptera littoralis*, Boisduval caterpillars, has been infectious to laboratory colony of *Kalotermes flavicollis*, they died after two days of infection (Al-Fazairy and Hassan, 1988). The principal factor influencing the efficacy of viral pathogens is the nature of the pest to be controlled. Smith (1967) revealed that many insects are antagonistic to termites that feed freely on the host plants.

It is difficult to infect the insects dwelling in soil which is an obscured environment. The effectiveness, specificity and secondary inoculum production make baculoviruses, desirable supplementary to broad-spectrum insecticides. They do not cause harmful effects on beneficial insects and other biological control agents; this makes them an important component of integrated pest management (IPM) (Cunningham, 1995). However, there are many disadvantages in the utilization of viruses to combat pest populations. The presence of virus particles in the soil is decreased by environmental factors such as rainfall and solar radiation. Also, they slowly eradicate their hosts. Further, the requirement of living hosts or tissue culture makes mass production of viruses are difficult. Finally, viruses find it challenging to combat other pest control agents such as chemical insecticides and microbes (Klein, 1988; Fuxa, 1990).

Application of Protozoa as Termititoxicants

Brooks (1988) found that the insect protozoan diseases are universal and have an important control role among insect populations. One of the most commonly detected species in *Microsporidia* is that their primary benefits are tenacity and regeneration in host species. (Henry, 1990) observed that the four protozoa groups that include insect-parasitic organisms, the phylum Microspora contain species that are most effective for insect control.

Desportes, (1963) identified a parasitic vermiform sporozoan protozoon in moist wood termite hemocoel *Zootermopsis*. No assessments have been published on the microbes' potential for termite control. Also, they easily alter in ambient conditions (Klein, 1988; Henry, 1990).

CONCLUSIONS

The extensive use of chemical based pesticides adversely affected the crops, as well as its microbial environment around the plant. There is a need to search potent pesticides against termites. Herbal and microbial components are effective alternatives as they kill the termites without any side effects on crops and other insects. The plant-based products like secondary metabolites and their by-products *viz*., oils and extracts reported to be more effective. The essential oil based termititoxicants showed promising results and could be used widely either in place of or as a supplement to commercially available synthetic termititoxicants. The microbes were used as antagonists against termites. Some fungi, bacteria and even viruses attack termites and destroy their colonial growth. These are now used in research trials and can be used widely as termititoxicants. The present study enlightened all the aspects of herbal and microbial components or organisms which can be effective termititoxicants in the coming era. Many industrial approaches are needed and many more are going on to make these plants and microbes based termititoxicants for termite management.

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