

1. Introduction

1.1 General biology of Termites

Termites (Isoptera) are terrestrial social insects with polymorphic highly organised colonies. These colonies develop around a nest system with division of labour among different castes. Nest systems vary from a single nest concentrated at one site to diffuse networks of subterranean galleries and chambers (Krishna and Weesner, 1969).

Termites are widely distributed throughout the tropical and sub-tropical regions, close to the equator, while fewer species live at higher latitudes. Some termite species extend their range of occurrence to the relatively cool zones of temperate regions (Emerson, 1955; Araujo, 1970; Wood and Johnson, 1986; Eggleton, 1999).

According to Snyder (1949), Emerson (1955), Krishna and Weesner (1970), and Pearce and Waite (1994) seven families of termites are recognised in the order Isoptera, namely Mastotermitidae, Hodotermitidae, Termopsidae, Kalotermitidae, Rhinotermitidae, Serritermitidae, and Termitidae, all together comprising to date more than 2600 species. The first six families are collectively known as lower termites. Members of the Termitidae are known as higher termites. This family is the most diverse, exhibiting a wide range of social specifications (Krishna and Weesner, 1970; Harris, 1971; Kambhampati and Eggleton, 2000).

Termites owe much of their ecological success and consequent economic importance to their highly developed social organisation (Stuart, 1969; Howse, 1970; Hermann, 1979; Sands, 1981). Colonies of termites consist of morphologically and functionally distinct castes. Three types of individuals can be distinguished: the reproductives, the workers and the soldiers. The reproductives are further divided into primary reproductives, which are responsible for the establishment of new colonies and secondary reproductives that act as

replacement reproductives (Lee and Wood, 1971; Lüscher, 1976). The workers and soldiers are sterile, wingless castes (Lee and Wood, 1971).

The workers are not sexually mature castes and are responsible for nest construction, foraging, caring for eggs, larvae, and royal pairs and maintain the fungus garden (in Macrotermitinae). Moreover, workers feed the larvae, soldiers and reproductive pairs, which are incapable of feeding by themselves (Noirot, 1974).

Soldiers are responsible for defending the colony and are characterised by their distinct head capsules. Their powerful mandibles enable them to defend the colony against many predators but prevent them from feeding themselves (Deligne *et al.*, 1981).

Caste ratios depend upon many internal as well as external factors. Workers are the most numerous castes whereas soldiers are often low in number.

In lower termites there are no true workers except for few species. These individuals are called pseudergates but in the following they will be referred to as “workers.” In general, pseudergates are thought to remain immature their entire lifetime. They can retain the potential of caste differentiation to soldiers or reproductives when required. The chemical message, which triggers those changes is secreted by soldiers and/or reproductives and spreads throughout the nest due to its volatile nature or is distributed by the termite individuals. It is acknowledged that the level of juvenile hormone (JH) secreted by the corpora allata at moulting determines the differentiation into workers and soldiers. Lüscher (1960) and later de Wilde and Beetsma (1982) suggested that low doses of JH induce the development into workers while high doses trigger soldiers’ development.

In higher termites the differentiation to any caste is determined before the first moult and appears to depend upon pheromones produced by the reproductives and the soldiers (Noirot, 1969; Okot-Kotber, 1985). It is generally accepted that developmental pathways differ greatly between different species.

Fig. 1 and 2 illustrate the basic scheme of development and the pathways for caste development in *Reticulitermes santonensis* (Feytaud) as an example of lower termites and in *Macrotermes* as an example of higher termites, respectively.

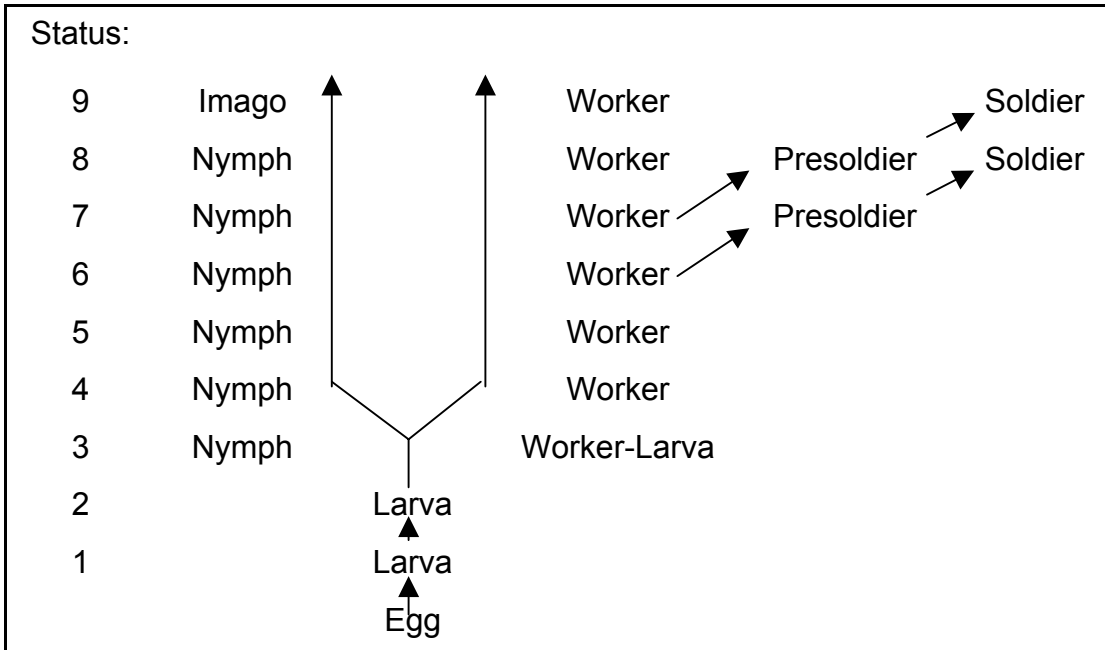


Fig. 1: *R. santonensis* (Rhinotermitidae) development summarised according to Noirot (1985).

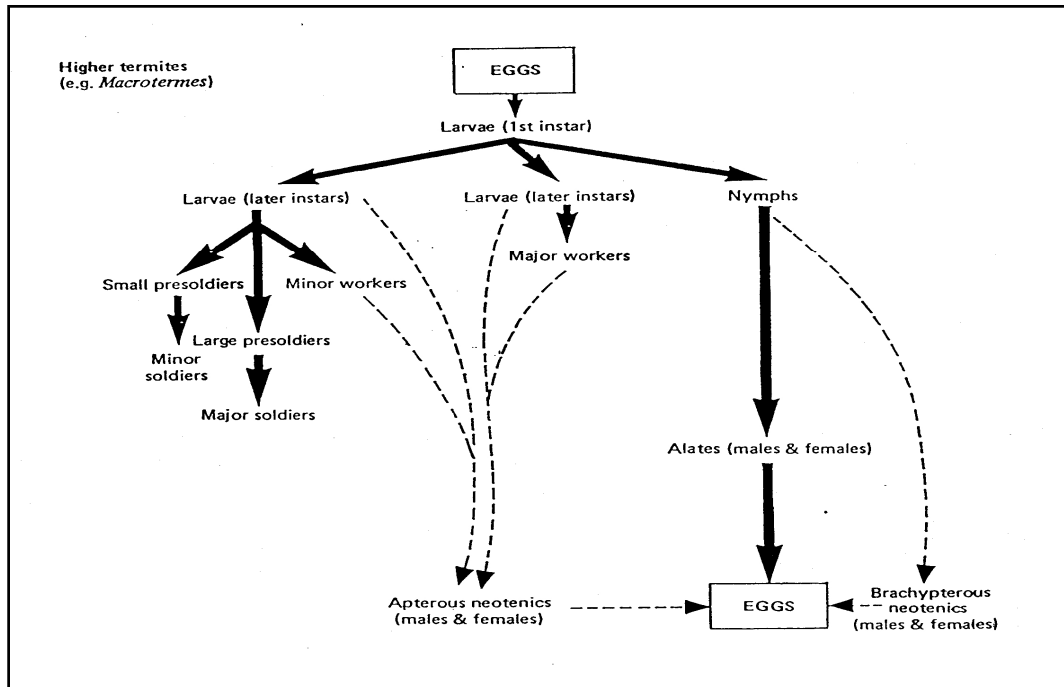


Fig. 2 : Caste pattern in the genus *Macrotermes* (Termitidae); summarised by Edward and Mill (1986).

Caste determination is generally regulated and geared to the needs of the colony (Haverty, 1977). However, this process is complex and differs between species.

Termites feed on a wide variety of food items including fresh, dead or decaying woody materials as well as dung and soil rich in organic matter (Waller and La Fage, 1987). Foraging workers are responsible for the collection and distribution of food within the colony (Lee and Wood, 1971). The workers feed the nymphs by trophallaxis, either by stomodeal, proctodeal food or from saliva secretions. Food digestion is completed with the aid of flagellates, protozoan symbionts, bacteria, or fungus gardens. Feeding habits and nest systems of termites significantly influence their diversity and population (Lee and Wood, 1971).

Three major nest types can be distinguished. Subterranean nests completely under ground level, epigeal nests protruding above the soil surface and arboreal nests built on a trunk or a branch of a tree but always linked to the soil by covered galleries. The location of the nest can change as the colony develops.

For dry wood termites the nest is built inside of wooden structures (Lee and Wood, 1971).

1.2 Termites as pests

Mill (1992), Aklatar and Shahid (1993), Wightman and Wightman (1994) and Wood (1996) intensively investigated the role of termites in agricultural systems. Today it is generally accepted that termites affect the vegetation in two ways, either by consuming living or dead vegetation or indirectly by modifying the physical and chemical properties of soil enhancing the soil nutrient level and soil water availability which influence the growth of the plants (Wood and Johnson, 1983; Lobry de Bruyn and Conacher, 1990; Logan *et al.*, 1992; Wood, 1996, Mando, 1997).

Termites have been recognised as pests a long time ago. Most of the research so far has focused on the assessment of damage inflicted by termites on the one hand and the development of control strategies on the other. In agriculture, termites were recorded to cause considerable damage to a large variety of crops such as groundnuts, sugarcane, cotton, cereals, date palm, coconut, cassava, yam, cocoa, and tea (Harris, 1968; Wood, 1996) in addition to forests and pastures (Logan *et al.*, 1990). The extent of damage caused by different species varies from insignificant to serious depending on the degree of infestation, the crop and the locality (Wood *et al.*, 1980 a, b; Johnson *et al.*, 1981;). Damage to buildings was recorded by Edward and Mill (1986). The cost of control was estimated up to 1.5 billions dollars annually in USA.

1.3 Insect growth regulators for termite control

For many years, control of termites relied mainly on the use of persistent chlorinated hydrocarbon compounds. However, the use of these insecticides was banned in many countries due to their negative impact on the environment and human health.

The search for alternative control methods to replace the conventional chemicals has been extensive ever since. A breakthrough has only recently been achieved with the development of biocides that act at concentrations below the detection threshold of the termites. Insect growth regulators (IGRs) such as juvenile hormone analogues (JHA) and chitin synthesis inhibitors (CSIs) are among the compounds tested for their effectiveness against termites. The results of many studies clearly indicated that both groups of compounds could suppress termite populations due to their slow mode of action, which is cumulative and non-repellent to termites (Su *et al.*, 1982). However, a tool to transport these chemicals beyond the site of application was needed. For this the baiting technique was adopted. It depends on the use of substrates that are accepted as food source for termites. Baits impregnated with biocides such as IGRs were investigated. After intensive experimental laboratory and fieldwork on the efficacy of the bait system their use is now widely accepted as a control means for termites (Su and Scheffrahn, 1989, 1993, 1996; Su *et al.*, 1995; Su, 1994; Forschler, 1996).

Juvenile hormone analogues act on the immature forms of termites by inducing moulting into soldiers (Jones, 1984; Su *et al.*, 1985; Haverty, *et al.*, 1989; Su and Scheffrahn, 1989). Laboratory work revealed that the use of JHA resulted in an excessive production of presoldiers that are unable to feed by themselves and rely mainly on workers to feed them. This over-burdens the feeding tasks of the workers, thus causing the death of the produced soldiers and ultimately leads to the nutritional collapse of the entire colony (Haverty, 1977; Hrdy *et al.*, 1979; Su and Scheffrahn, 1990). Results obtained by Jones (1989) from both laboratory and field studies revealed that JHAs have especially significant effects on colonies with naturally lower numbers of soldiers (1-2%) as in *Reticulitermes* species compared with those having a high proportion of presoldiers. Studies so far mostly focus on lower termites and higher termites have been studied only rarely.

Chitin synthesis inhibitors (CSIs) are slow acting compounds having no contact insecticidal properties with cumulative effects over time (Pallaske, 1997). Generally CSIs act on insects by disturbing the deposition of chitin of the insect cuticle so that the moulting process is inhibited and the postembryonic development will be stopped. Studies carried out by Sowa and Marks (1975) and Verloop and Ferell (1977) concluded that the accumulation of the CSIs is restricted to arthropods so that no bioaccumulation takes place in aquatic and terrestrial food chains.

The role of chitin synthesis inhibitors to control termites was examined by Doppelreiter (1981) and Fragalla *et al.* (1985). Their results indicated that diflubenzuron (Dimilin) caused ecdysis inhibition in *Heterotermes indicola*, *Reticulitermes flavipes* as well as *Microcerotermes* species. Similar results were also obtained by Su and Scheffrahn (1993, 1996) on *R. flavipes*. However, field studies revealed that only hexaflumuron caused significant ecdysis inhibition in many of the economically important subterranean termite species (Su and Scheffrahn 1993, 1996). Recently, a new chitin synthesis inhibitor, flufenoxuron, has been developed by the industry. It has been tested on some insect species, but its potential to control termites has not yet been investigated.

On higher termites, the influence of growth regulators was first reported by French (1974) on *Nasutitermes exitiosus* and later by Lenz (1976) on *N. nigriceps*. They confirmed the role of soldier induction on the mound-building termites. Similar results were obtained by Okot-Kotber (1980 a and b) on laboratory colonies of *Macrotermes michaelseni* (Macrotermitinae, fungus growing). He observed that under the influence of JHA the larvae could differentiate into presoldiers. However, little is known about the mechanism in regulating caste differentiation in fungus growing subterranean termites.

In these studies two compounds, fenoxycarb and flufenoxuron were tested for their effectiveness against termites. Janssen Pharmaceutica, Belgium, supplied both compounds. Fenoxycarb is a phenoxy-ethyl-carbamate insect growth regulator with strong juvenile hormone action. It acts on the insects while

moulting from one larval stage to the next and/or prevents the first instar larvae from hatching from eggs. Flufenoxuron is an acylurea insect growth regulator that acts as chitin synthesis inhibitor (CSI) by disrupting chitin deposition in the insect cuticle.

The present work focuses on the following objectives:

- i) To determine the general effect of the JHA fenoxycarb (mortality, feeding deterrence, presoldier production, decrease of fecundity) and proper methodology of application to control *R. santonensis* lower termites.
- ii) To test the transferability of fenoxycarb via trophallaxis and its distribution through the entire colony.
- iii) To determine the general effect of the CSI flufenoxuron (mortality, feeding deterrence, chitin synthesis inhibition) to control *R. santonensis* lower termites.
- iv) To determine the possible synergistic effect of both fenoxycarb (JHA) and flufenoxuron (CSI) when combined together.
- v) To determine the acceptance of fenoxycarb and flufenoxuron on *Microtermes* (Termitidae) in the field.