FOOD PREFERENCE, FORAGING ACTIVITY AND VIRTUAL BAITING OF THE FOREST FIRE ANT, *Tetraponera rufonigra* (JERDON) (HYMENOPTERA: FORMICIDAE)

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by

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ABSTRAK

Disertasi ini tertumpu kepada kajian kegemaran makanan, pencarian makanan, anggaran populasi serta kawalan semut api hutan, *Tetraponera rufonigra* (Jerdon). Di antara jenis makanan lipid yang berlainan, *T. rufonigra* paling mengemari telur kuning ($P < 0.05$). Tetapi mereka tidak menunjukkan pilihan khusus terhadap jenis makanan karbohidrat dan protein yang berlainan yang diberikan ($P > 0.05$). Apabila makanan yang paling digemari daripada setiap tiga kelas makanan yang diberikan, semut api hutan lebih mengemari makanan berkarbohidrat (sukrosa) daripada makanan berprotein tinggi (tuna) dan makanan berlipid (telur kuning) ($P < 0.05$). Kualiti makanan tidak mempengaruhi pilihan makanan semut api. Semut api tertarik kepada larutan sukurosa pada kepekatan 60% sehingga hingga 20% ($P < 0.05$). Aktiviti pencarian makanan *T. rufonigra* adalah berkadar songsang dengan kelembapan persekitaran ($y = -2.5651x + 235.28$, $r^2 = 0.525$, $P < 0.05$) tetapi adalah berkadar langsung dengan suhu persekitaran ($y = 11.22x - 288.36$, $r^2 = 0.7304$, $P < 0.05$). Kemuncak aktiviti pencarian makanan direkod di antara jam 0800 dan 1800. Semut ini didapati mencari makanan jauh dari sarang pada anggaran purata jarak, 46 ± 8.4 m (mean ± SEM, $n = 4$) dan pencarian makanan mereka melingkungi kawasan seluas purata, 2,082.5 ± 202.7 m^2

(mean ± SEM, *n* = 4). Walaubagaimana pun, aktiviti pencarian makanan mereka dipengaruhi oleh kewujudan species semut lain yang mungkin mempengaruhi jarak dan kawasan pencarian makanan sepertimana yang diperhatikan dalam kajian ini. Populasi pencari makanan *T. rufonigra* untuk koloni yang matang boleh mencapai lebih daripada 2,000 individu. Tiga jenis insektisida, iaitu indoxacarb, fipronil dan deltamethrin, yang diuji terhadap *T. rufonigra* menghasilkan 70-98% pengurangan semut sehari selepas rawatan. Hampir kesemua bilangan pencari makanan didapati telah berkurangan dalam masa tiga hari dengan rawatan fipronil. Walau bagaimanapun, indoxacarb dan deltamethrin didapati tidak berkesan terhadap penghapusan koloni *T. rufonigra*. Sungguhpun terdapat, pengurangan sebanyak 70-80% dalam masa satu hari selepas rawatan, bilangan pencari makanan meningkat pada keesokan harinya.

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ABSTRACT

This dissertation focuses on the feeding preference, foraging behavior, population estimation, as well as control of the forest fire ant, *Tetraponera rufonigra* (Jerdon). Among different types of lipid food provided, *T. rufonigra* preferred egg yolk the most ($P < 0.05$). However, they did not show any specific preference toward different choices of carbohydrate and proteinaceous foods that were provided ($P > 0.05$). When their most preferred food from each of the three food class was selected, they showed higher preference for carbohydrate-base food (sucrose) than those of protein-rich food (tuna) and lipid-base food (egg yolk) ($P < 0.05$). Qualities of food did not affect much on their feeding preference. They were attracted to the sucrose solution from 60% to as low as 20% concentration ($P < 0.05$). Foraging activity rhythm of *T. rufonigra* was negatively correlated with ambient relative humidity ($y = - 2.5651x + 235.28$, $r^2 = 0.525$, $P < 0.05$) but positively correlated with ambient temperature ($y = 11.22x - 288.36$, $r^2 = 0.7304$, $P < 0.05$). Peak activities were recorded between 0800 hours and 1800 hours. It could forage over a distance of 46 ± 8.4m (mean ± SEM, $n = 4$) and a foraging territory of 2,082.5 ± 202.7m^2 (mean ± SEM, $n = 4$). Nevertheless, its foraging activity was found to be affected by the presence of other ant species. This could have delimitated its foraging distance and territory as observed in this study. The foraging population could reach more than 2,000 for a mature colony of *T. rufonigra*. Three insecticides namely indoxacarb, fipronil, and deltamethrin, which were tested against *T. rufonigra* showed 70-98% reduction of foragers after 1 day post-treatment. Almost complete reduction of foragers was achieved within three days for fipronil. However, indoxacarb and deltamethrin were not effective to eliminate *T. rufonigra* colonies. Although 70-80% reduction was observed after 1 day post-treatment, the number of foragers increased at the following days.

CHAPTER ONE

GENERAL INTRODUCTION

Ants thrive in abundance in the terrestrial world as the premier soil turner, channels of energy, dominatrices of the insect fauna. Recent measurement of the modern insect fauna suggested that about one-third of the entire animal biomass of Amazonia *terra firme* rain forest is composed of ants and termite. In a hectare of soil, there are an excess of 8 millions ants and 1 million termites. Together with bees and wasps, they make up more than 75% of the total insect biomass (Fittkau and Klinge 1973). Similar domination of ants and termites was also observed in the forests and savannas of Zaïre (Hölldobler and Wilson 1990).

Ants are a superorganism with its own homeostatic responses and flexibility in behavior such as thermoregulation of nests and control of humidity. They employ most complex form of chemical communication of any animals. Their social organization striking by resembles the early development of human societies, designated as hunting, pastoral, and agricultural (Lubbock 1894). Species such as *Formica fusca*, live in comparatively small communities and less develop among them. They hunt singly and feed partially on the honey-dew of aphids but not domesticate these insects, resembling the hunting phase of human societies (Hölldobler and Wilson 1990). Some species like *Lasius flavus* show skilfulness in building their mounds. They have higher number in their communities and establish more complex system of communication. They have domesticated certain species of aphids and are comparable with the pastoral stage of human progress (Hölldobler and Wilson 1990). Lastly, the agricultural nations can be represented by the harvesting ants (Hölldobler and Wilson 1990).

Ants are social insects with extraordinarily complex social systems; serve as a good model for optimization studies of sociobiolgy. Ant workers have well-defined tasks and anatomical structures. As dominant insects, ants are present in rich species, subspecies and variety. However, ants of different species have very different economic importance. Some are highly beneficial, others are highly injurious to human. They interfere with human through their feeding behavior, adaptation to establish their colonies indoor or around the perimeter of structure, and aggressive stinging and biting habits (Wheeler 1910). Some species even have potential to act as mechanical vectors for various pathogenic organisms (Lee and Tan 2004). When they are present indoors and outdoors in sufficient numbers to be a nuisance as well as disrupting the human living comfort, man struggles to control them.

Tetraponera spp. from the family Formicidae, are characterised by their arboreal nature and slender bodies. They live mutually in hollow structures of plants and trees, such as thorns or branches. Different species of *Tetraponera* are associated with different plant species. These hosts are known as myrmecophytes. Acacias is the most common myrmecophytes for *Tetraponera.* All *Tetraponera* protect their host plants from intrusion of other insects to reduce resource competition for their host through aggressive nature and by trimming leaves/branches of neighbouring plants. Once they detect invaders, sophisticated chemical signalling systems will allow *Tetraponera* to quickly outnumber and overpower any invaders. To expand their colony, a queen with a number of workers will leave the old host plant to establish a new colony.

The forest fire ant (also known as arboreal bicoloured ant, semut Selangor or semut api hutan in Bahasa Melayu), *Tetraponera rufonigra* (Jerdon, 1851) is one of the most common *Pseudomyrmicine* species found in the tropics, especially in the Indo-Australian region (e.g. India, Pakistan, Sri Lanka, Bangladesh, Thailand, Malaysia, Singapore, South to Sumatra and Java, Southern China, Seychelles etc.) (Jerdon 1851, Rickson and Rickson 1998, Ward 2001, Lee and Tan 2004, Hannan 2008, Kumar and Mishra 2008, Piromrat et al. 2008). It is gaining notoriety as an increasingly important pest ant in the urban environment such as schools, nursing homes, temples, parks and gardens (Lee and Tan 2004). It is known for its extremely sharp and painful sting and bite. Its venom also causes anaphylaxis (Wanotayan 2005, Piromrat et al. 2008) that may threaten human health.

An effective but less environmental contamination and ecological injury control method toward *T. rufonigra* is needed. Baiting is currently a popular method for control of ant infestations and has been studied broadly with several species of ants (Klotz and Williams 1995, Cornelius et al. 1996, Hooper-Bùi and Rust 2000, Silverman and Roulston 2001). This approach utilizes the natural foraging and social behavior to reduce infestations and provides suppression of the entire colony (Knight and Rust 1991, Williams and Vail 1993, Klotz et al. 1997).

The success of baiting against the targeted ant species depends on the attractiveness and palatability of the bait matrices and the toxicant formulated in the baits has an extended speed of kill so that the foragers have enough time to distribute it to the entire colony (Knight and Rust 1991, Klotz et al. 2000). Feeding preferences are different amongst ant species, the attractiveness and palatability of food materials used in the bait matrices have not been comprehensively studied. It is not surprising that little attention has been placed on *T. rufonigra*.

The objectives of this study are:

1. To examine the feeding preferences of *T. rufonigra* with different food types and food qualities.
2. To study the foraging behavior of *T. rufonigra* including the foraging activity, foraging distance and territory.
3. To estimate the foraging population of *T. rufonigra*.
4. To determine the effectiveness of several insecticide compounds against *T. rufonigra* by the use of virtual baiting technique.

CHAPTER TWO

LITERATURE REVIEW

2.1 Ants in general

Ants evolved from wasp-like ancestors in the mid-Cretaceous period between 110 and 130 million years ago and diversified after the rise of flowering plants (Grimaldi and Agosti 2001, Wilson and Hölldobler 2005, Moreau et al. 2006). They belong to the family Formicidae, a member of the order Hymenoptera. Ants are very successful social insects with fantastic adaptability and plasticity common to man and other organisms (Wheeler, 1910). They have remarkable longevity and numerical ascendancy in their individuals. Worker ants are known to live from four to seven years and queens from thirteen to fifteen years. They are widely distributed from the arctic regions to the tropics and occupy wide range of ecological niches. They present in great number of species, subspecies and varieties. To date, more than 12,500 out of an estimated total of 22,000 species have been classified.

Ants are important in the decomposition of organic substances and conservation of the stability of our ecosystem. Many human cultures make use of ants in cuisine, medication and rituals. Some species are valued in their role as biological pest control agents. However, their ability to exploit resources brings ants into conflict with humans, as they can damage crops and invade buildings. Their stinging and biting habits especially cause nuisance to human.

There is great interest studying the variation and geographical distribution of ants, the extraordinary phenomena of ants' polymorphism, parthenogenesis and sex-determination. Although only less than 0.5% out of the identified ant species are noxious to human, studies of the control and management has been carried out to eliminate this pest from our living structures (Lee and Robinson 2001).

2.2 The development of ants

Ants develop by complete metamorphosis (holometabolous). They start from eggs and hatche into larvae. The larvae are fragile and largely immobile. Thus, they need nursing from the workers and are fed by workers through trophallaxis. These larvae will undergo a pupal stage before emerging as an adult. The developmental environment of larvae and pupae need to be kept at constant temperatures to ensure proper development, and so are often moved around the various brood chambers within the colony (Hölldobler and Wilson 1990). Ants live in societies that cooperate in many aspects and thus, form colonies in order to ensure and maintain the successful survivorship. An ant society has division of labour, ability to communicate between individuals, and solve complex problems.

A simplest caste and communication system can be achieved with a few dozen predatory individuals living in small natural cavities. But some highly organized colonies consist of millions of individuals and may occupy large territories. The life cycle of an ant colony can be divided into three stages: the founding stage, the ergonomic stage and the reproductive stage (Oster and Wilson 1978).

A broad range of reproductive strategies have been noted in ant species. Typically, winged males and females leave the colony during the species specific breeding period. Males take flight before the females, find a common mating ground and then secrete a mating pheromone to attract the females. After mating, the independent queen will seek a suitable nest site to begin the founding stage of a colony; male usually die within two weeks (Haack and Granovsky 1990). The queen sheds her wings, lays and rears her first brood until the first batch of workers take over the task. Most ant species consist of multiple queens in a colony (polygynous) while some other species have only a single queen in a colony (monogynous). The female alate is able to continuously reproduce throughout her life once it mates (Lee

2004). Alates in certain species are able to reproduce asexually through thelytokous parthenogenesis (Heinze and Tsuji 1995).

The colony enters ergonomic stage when the first batch workers eclose as adults. At this phase, activities focus on maximizing the growth of the worker population. Workers devote themselves to take over the task of feeding, foraging, nest enlargement and brood care while the queen reverts herself exclusively to egg-laying. In this period, colony-level selection is paramount and a closely programmed division of labor is established. Ergonomic analysis of ant colonies reveals a range of tasks and roles, allocated between different castes. Workers in most of the species are monomorphic (same size). Younger workers normally remain in the nest taking care of the queen and brood while the older workers forage for food and defend the colony (Haack and Granovsky 1990). In some species, workers are subdivided in two sizes (dimorphic): minor and major or in multiple sizes (polymorphic): minim, minor and major. Minim workers usually take charge on lighter tasks such as tending the queen and brood. Major workers are highly specialized and responsible on foraging, constructing nest and defending against enemies. Minor workers are more flexible. They tend the nest or forage for food (Lee and Chong 2003). There are often temporal castes, with roles changing over individual lifetimes. Caste determination is complex, but colony demographics are clearly adaptive. All the workers are sterile females.

When the colony reaches to a mature colony size, reproductive stage is initiated. Production of new queens and males becomes active. In some species, the caste differentiation of larvae into queens and workers is influenced by the nutrition intake. Genetic influences and the control of gene expression by the developmental environment are complex and the determination of caste continues to be a subject of research (Anderson et al. 2008). During the species specific breeding period, new reproductives swarm out from the nest, mate and establish a new colony. After the nuptaial flights of the newly formed reproductives, the mother colony will either die or temporarily return to the ergonomic stage (Oster and Wilson 1978). Besides swarming, ants can establish a new colony through budding, where several mated queens together with a group of workers carrying the brood move to a new site (Lee and Chong 2003). Sometimes, instead of queens, workers are able to start a new colony by special feeding of the larvae (Lee and Chong 2003).

2.3 Feeding behavior of ants

Ants feed on a wide range of resources that are available in their habitat, for example: honeydew from plant lice, insect prey, sap and resin, fungi, carrion and seeds. However, diet of some ants is not as catholic. They show great dietary specialization and generalization. The efficient natural selection of food by foragers is to maximize a colony’s energy intake (Oster and Wilson 1978). The differential food distribution in ants depends on the colony age, stage and presence of brood because different food types have different functions (Abbott 1978, Stein et al. 1990).

In nature, different food types contain different essential macronutrients. For example, ants can obtain proteins and lipids from a varied diet of insect prey; carbohydrates from nectar in plants, honeydew from aphids, scale insects or mealybugs (Nash 1969). These macronutrients provide the vast majority of metabolic energy to ants. Proteins are essential for growth and development as they can be used for building, maintaining and repairing body tissues. Thus, they are needed by the reproductive castes, growing larvae and after metamorphosis in the case of gynes (Peakin 1972). Lipids are important reserve sources and are given to the larvae to store. Protein and lipid are the two most crucial nutrients to ensure healthy and continuous production of brood in an ant colony. Hence, when a colony is in a productive stage where there are a lot of brood in the colony, the foragers tend to forage more towards proteinaceous and lipid foods (Stradling 1978). Carbohydrates serve as the main energy source that is more needed by workers who drive the society of colony.

On the whole, the intake and food selection in a colony principally depends on the presence and development of brood. They are usually the first to be fed by the foragers returning to the nest with food before distributing of the nutrients to the rest the of colony members through trophallaxis. Trophallaxis (food exchange activity) is one of the main mechanisms for integration between members of a large and complex colony (McMahan 1963). It is important to provide nourishment for the colony members that cannot or do not forage including domestic workers, queens, reproductive and larvae. Trophallaxis is an open system and the flow is not limited to one way. Each worker can share food with an unlimited number of nestmates (Wilson 1971), foragers feed each other and foragers may be fed by domestic workers. Such repeated exchanges are able to keep the workers informed and aware of the nutritional status of the colony so that foragers can assess the degree of colony hunger and respond accordingly.

Food selection and recruitment are also related to quantity, quality and the location of food source (Nonacs and Dill 1990, Nonacs and Soriano 1998). According to Hölldobler (1976), the definition of food quality is different to an ant colony depending on the size and concentration of source, distance of source from the nest, as well as the degree of colony starvation. The foraging population of a colony is often large and sometimes polymorphic, and worker foraging activity is severely constrained by temperature (Reyes Lopez 1987). Food selection in ants showed varying degrees of correspondence among different food types (Mirenda and Topoff 1980, Bowers and Porter 1981, Rissing 1981, Rudolph and Loudon 1986, Howard 1987, Sudd 1987, Traniello 1989).

The seed-harvester ants, *Pogonomyrmex rugosus* and *Pogonomyrmex barbatus*, increased diet specialization with increasing distance of seed patches from the nest by selecting large seeds (Davidson 1978). On the other hand, *P. occidentalis* and *Pogonomyrmecxa lifornicus* showed no significant change in the choice of seed size in correlation with distance (Taylor 1976, Holder Bailey and Polis 1987). Higher profitable or quality of food allows the ants to maximize the net rate of energy delivery to the nest (Davidson 1978). When the distance from nest increases, the cost of travel and transport also increases. Conversely, the net energy value of seeds decreases. Ant selects large seeds to compromise the energy lost and maximize the energy gained. However, foraging costs for *P. occidentalis* workers are less than 0.1% of the caloric content of an average collected seed (Fewell 1988). In this case feeding selectivity may not change substantially with increasing travel costs but time cost and net energetic gain rate are the important criteria in foraging strategy (Fewell 1988).

According to Howard and Tschinkel (1981), liquid comprise a major portion and form an important part of the diet in many social insects. Most of the ant species prefer liquid food. As reported in Stradling (1978), 81% of the food intake in *Formica rufa* (Linnaeus) was liquid food and the balance of 19% was solid food. There are two parameters which appear to determine the liquid feeding in ants: the existence of trophallaxis or a comparable liquid food exchange, and the associated temporal store of liquids collected during foraging and the existence of a well-developed crop (social stomach) that enable them to regurgitate the food to the larvae and other adult nest metes (Paul and Roces 2003).

Whether it is the crop contents of worker ants or the contents of the post pharyngeal gland, liquid food is most common in the larval diet of many species. These droplets are regurgitated and placed on the mouthparts of the larvae (Abbott

1978). Interestingly, in an ant colony, only larvae are capable in digesting solid food and enriching the nutrients. Workers generally feed solid protein food directly to larvae because they are lacking the necessary endopetidase in their foregut to digest them (Stradling 1978). Workers place the fragments of solid food on the mouthparts of mature larvae or at the antero-ventral region of fourth instars larvae which are morphologically adapted to feed on solid food (Petralia and Vinson 1978, Lim et al. 2005). In return, workers receive the protein by feeding on larval secretions (Nonacs 1991).

Workers in numerous species apparently cannibalize healthy larvae even though food in the colony is still sufficient (Sorensen et al. 1983). For instance, workers of *Camponotus floridanus* (Buckley) cannibalized larvae when the ratio of larvae over workers is too high, or in respond to discernment of increasing danger for foraging. Certain species such as *Plagiolepis pygmaea* Latreille, *Aphaenogaster subterranean*, *Temnothoraz recedens* and *Myrmica rubra* (L.) produce two types of eggs: reproductive eggs and trophic eggs (Glancey et al. 1973, Abbott 1978). Trophic eggs are rich in protein, non-viable and serve as food.

2.4 Foraging behavior of ants

Ant foraging is a collective process composed of the activities of individuals as well as behaviorally integrated groups. In an ant colony, only about 10-20% of the colony members are taking part in the foraging activity (Petal 1978). A forager leaves the nest in either a random or a consistent direction. A travel phase ensues, during which the worker maintains a constant compass bearing and moves directly away from the nest. At some point during the travel phase the forager shows a high frequency of turning, marking the beginning of search. When food resources are encountered, selection will be based on a forager's physical caste, age, and prior experience, the trip distance, thermal stress, resource quality, and the colony's current nutritional status. Depending on the ant species and the size, density, or quality of the food, the forager may communicate information to nestmates about its location and recruit additional foragers.

Communication among individuals is of paramount importance as a control mechanism of colony-level foraging responses. It mediates cooperation among foragers during search and selection of food resources. Foraging responses of ants may change according to nutritional demands of the colony (Sudd and Sudd 1985), food type (Detrain and Deneubourg 1997), spatio-temporal distribution of food, food size (Hölldobler 1976), food quality (Hölldobler and Wilson 1990), and food density (Bernstein 1975). Effective communication provides regulatory feedback during the daily and seasonal organization of foraging, and coordinate individual behavior into mass action.

Total expression of a colony's foraging strategy involves a series of components behavior that may each have individual, social, and ecological influences and that have all evolved in response to resource distribution patterns, competition, and predation. Various foraging traits have been reported among different ant species. For instance, 'diffuse foraging' occurs in more primitive subfamilies (e.g. Ponerinae and Myrmicinae) (Oster and Wilson 1978). Foragers leave the nest singly and retrieve food solitarily. They apply simpler recruitment strategies such as 'tandem recruitment' or 'group recruitment'. In 'tandem recruitment' forager gives signal to another member by direct physical interaction while 'group recruitment' involves chemical signalling by one forager to recruit a few members when the forager found a food source. On the other hand, more advance recruitment system takes place in advanced subfamily (e.g. Formicinae). Although the formicines *Cataglyphis* spp. and *Ocymyrmex* spp. also collect randomly dispersed food largely through individual effort (Wehner 1987, Wehner et al. 1983), but they have pheromone mediated cooperative foraging (Lee and Chong 2003). They recruit other foragers to the food source through independent pheromone trail-laying and trail following behavior, named ‘mass recruitment’ system (Chadab and Rettenmeyer 1975).

Ants are poikilothermic, and their foraging activity is therefore constrained by ambient temperature or soil temperature (Bernstein 1974, Peakin and Josens 1978, Traniello 1989, Porter and Tschinkel 1993), water stress, (Traniello 1989), moisture, radiation, wind (Pol and de Casenave 2004), and other physical factors that might affect the energetic costs of foraging or the use of time. Several studies have demonstrated a significant effect of ambient temperature on metabolic rate as measured by oxygen consumption (Davison 1978, Peakin and Josens 1978), water loss and transport costs of the foraging ants (López et al. 1992). In *F. schaufussi* the elevated rate of oxygen consumption appears to be an important component of foraging cost that influences prey selection (Traniello et al. 1984). The foraging activity of *Camponotus pennsylvanicus* (De Geer) is significantly correlated with temperature, night length, and wind speed. It will travel faster as temperature increases (Nuss et al. 2005). Thus, ants will display rhythm in their foraging activity (Saunders 1982).

Ants may be night-active (nocturnal), day-active (diurnal) or twilight-active (crepuscular). Beside exogenous cues as discussed above (i.e. a direct response to environmental cues), the rhythm of foraging activity is controlled by endogenous cues (i.e. an underlying circadian oscillation, which are part of the physiological make-up of the organism) (Saunders 1982). If ants are imprisoned in the dark at a constant temperature, they will show peaks of activity at the same time of day (Sudd 1967). This phenomenon is cause by the internal 'biological clock' of the ants through their experience and time sense. Biological clocks control a wide variety of behavioral and physiological activities including daily rhythms of locomotion, feeding, mating, oviposition, pupation and eclosion. Virtually, all organisms possess endogenous daily clocks that enable them to prepare in advance to the cyclic 24 hours changes in the environment (Saunders 1976).

An ant colony is generally sessile, the resource and competitive environment is in essence defined by its location. Therefore, foragers must have spatially foraging pattern to harvest food efficiently and minimize competition (Traniello 1989). The significance of the spacing patterns of ant colonies and the division of foraging area has chiefly been approached by measuring dispersion and/or by studying territorial interactions (Hölldobler and Lumsden 1980, Levings and Traniello 1982.).

Cost/benefit explanations suggest interplay of the economics of foraging and defense and allow predictions to be made about how colonies should allocate workers to related tasks in time and space (Hölldobler and Lumsden 1980, Johnson et al. 1987). At both individual and colony-wide search patterns, resource distribution in space and time, and competition are the major influences on the organization of search.

2.5 Control of ants

The principal objectives of ant control programmes are to diminish ant activities and to exterminate the colonies (Hedges 1998). However, controlling ant infestations present significant problems in many urban areas. Different ant species show variations in their biology and behavior. Thus, it is impossible to have a universal solution for ant control.

Residual insecticide treatment is the best method to eliminate the ant colony if the nesting site can be located. When this method is required, a non-repellent insecticide should be used. It is because repellent insecticides such as pyrethroids may incur budding which would create an even larger infestation problem. Residual treatment is not effective on foraging ants. Total elimination of a colony could not be achieved because the visible foragers only comprised 5 to 10% of the entire ant population (Adams et al. 1999). Perimeter treatment is useful for preventing invasion of ants from outdoors. Both repellent and non-repellent insecticides can be used (Lee and Tan 2004). Dust treatment can be used against ants that nest inside switchboxes, motor, wood structures, wall voids, cracks and crevices to replace sprays for dry areas (Lee and Tan 2004).

Baiting is another alternative method if the ant colony cannot be located. This method is getting popular and has been studied extensively with several species of ants (Knight and Rust 1991, Cornelius et al. 1996, Ipser and Gradner 2004, Warner and Scheffrahn 2005). It requires minimal amount of insecticides and can be applied to sensitive areas such as zoos, children centres and computer rooms (Lee and Yap 2003). Baiting exploits the ants' food-sharing behavior (trophallaxis) to ensure that the toxicant from baits is circulated among other colony members. Therefore, the active ingredient in baits should be strong enough to achieve ant mortality yet slow-acting so that a sufficient lethal dose is transported back to the nest and transfer to other colony members before toxicity effects are exhibited. The toxicant must be effective over more or less 10-fold range of the concentration because it will be diluted through trophallaxis and the amounts of toxicant will be much lesser than the amount that the foragers fed on (Hooper-Bùi et al. 2002). Besides, the active ingredients must be formulated into a palatable food attractant that would not deter feeding, environmentally safe and display low mammalian toxicity.

An effective bait formulation must contain an attractive and appetizing food carrier. The bait must be able to compete with other food sources in the infested area. It is also crucial to place attention on the varied food preference of different ant species that could be due to periodical or seasonal changes (Edwards and Abraham 1990), changes within the ant colonies or satiation effects. These could be overcome by using dual-attractant baits (Lee et al. 2002), periodical bait-switching plans or introducing pheromonal compounds into the bait (Greenberg and Klotz 2000). Besides, the palatability of the physical features of the baits should be formulated in suitable forms that would encourage feeding by the target species. Some ants prefer granular baits while most go for semi-liquid gel or paste-based baits (Lee et al. 2002).

Baits should be placed on the ant trails and as closely as possible to the ant colony where the ants can immediately find the baits (Lee and Chong 2003). All potential competing food and water sources that may affect bait-feeding must be removed (Hedges 1998). Contact insecticides should never be used during the employment of bait treatments as this would be counter-productive. Reduction in the worker population would only disrupt the transport of bait material back to the colony, reducing the efficacy of the bait.

Fipronil is an insecticide discovered and developed by Rhône-Poulenc between 1985 and 1987. It was placed on the market in 1993. Fipronil is a broad-spectrum phenylpyrazole insecticide that disrupts the insect central nervous system by blocking the passage of chloride ions through the γ-aminobutyric acid-gated (GABA) receptor and glutamate-gated chloride channels (GluCl), components of the central nervous system (Tingle et al. 2000). This causes hyperexcitation of contaminated insects' nerves and muscles which results in death (Cole et al. 1993). It is much sensitive in insects compared to mammals (Hainzl and Casida 1996). This may due to fipronil having a better efficacy on GABA receptor, and furthermore, GluCl does not exist in mammals (Raymond-Delpech 2005). The International Union of Pure and Applied Chemistry (IUPAC) name for fipronil is (±)-5-amino-1-(2,6-dichloro-α,α,α-trifluoro-*p*-tolyl)-4-trifluoromethylsulfinylpyrazole-3-carbonitrile (Fig. 2.1). It has been proven as an effective insecticide against many insect pests including ants, termites and cockroaches. It is a slow acting and non-repellent insecticide which can act as a stomach poison or contact poison (Soeprono and Rust

2004, Klotz et al. 2007). When mixed with bait, it allows the poisoned insect to return to the colony and transfer the toxic to the nestmates.

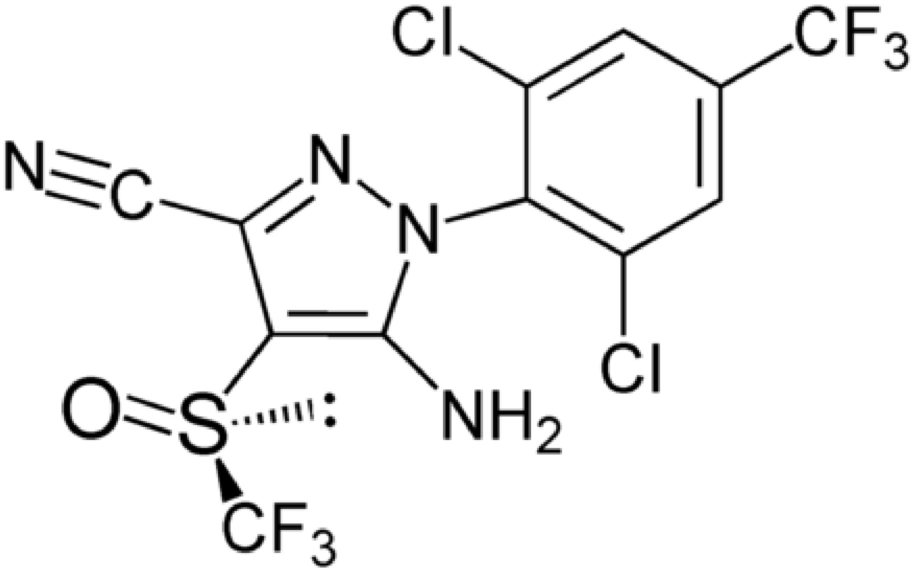

Fig. 2.1 Structure of fipronil.

Indoxacarb is the International Organization for Standardization (ISO) approved novel oxadiazine insecticide. The International Union of Pure and Applied Chemistry (IUPAC) name for fipronil is methyl (*S*)-*N*-[7-chloro-2,3,4a,5-tetrahydro-4a-(methoxycarbonyl)-indeno[1,2-*e*][1,3,4]oxadiazin-2-ylcarbonyl]-4’ (trifluoromethoxy)carbanilate (Fig. 2.2). Indoxacarb is designated by the European Union or United States Environmental Protection Agency (EPA) to be a "reducedrisk" pesticide and is considered an organophosphate (OP) replacement. It is highly toxic to insects but low toxicity to mammals, birds, earthworms and aquatic organisms. It does not cause mutagenic, carcinogenic, developmental, or reproductive effects. Some neurotoxicity was present, but often at fatal doses. It is a broadspectrum insecticide that is effective against codling moth, white apple leafhopper, pandemic leafroller and lacanobia fruitworm (McKinley et al. 2002). It acts on the sodium channels, neuronal nicotinic acetylcholine receptors and GABA receptors (Narahashi 2001). It blocks off the insect voltage-gated sodium channel by the N-decarbomethoxyllated metabolite (Wing et al. 2000). As a result, the insect will cease feeding, become paralysed and eventually die (McKinley et al. 2002). Indoxacrab must first be metabolized by the insect into an N-decarbomethoxyllated metabolite in order to become acutely toxic (Furman and Gold 2006b). It can act as contact and stomach poison (Moncada 2003).