# BEHAVIORAL RESPONSES OF THE GERMAN COCKROACH, *BLATTELLA GERMANICA* (L.) (DICTYOPTERA: BLATTELLIDAE) TOWARDS TOXIC BAITS

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**by**

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The following abbreviations have been used commonly throughout this thesis:

| | |
|---|---|
| ANOVA | Analysis of variance |
| Df | Degree of freedom |
| FL | Fiducial limits |
| IPM | Integrated pest management |
| LT | Lethal time |
| RH | Relative humidity |
| SE | Standard error |
| SEM | Standard error mean |

# RESPON KELAKUAN DAN TOKSIKOLOGI LIPAS JERMAN, *BLATTELLA GERMANICA* (L) (DICTYOPTERA: BLATTELLIDAE) TERHADAP UMPAN RACUN.

## ABSTRAK

Kajian ini bertumpu ke atas keracunan berbandingan beberapa racun serangga umpan gel perhubungan antara kelakuan makan lipas Jerman, *Blattlla germanica* (L.) den keracunan umpan. Kajian arena telah dilakukan untuk mengkaji keberkesanan umpan gel terhadap tiga peringkat hidup lipas Jerman: dewasa jantan, dewasa betina dan nimfa. Sejumlah lima jenis umpan racun komersial telah diuji dan keberkesanannya dinilai dengan membandingkan nilai $LT_{50}$ dan $LT_{95}$ racun tersebut. Susunan ketosikan umpan racun yang bermula daripada nilai yang terendah kepada nilai yang tertinggi mengikut nilai $LT_{50}$ ($p = 0.05$) ialah: fipronil = indoxacarb > imidacloprid > abamectin > hydromethylnon. Walau bagaimanapun, susunan nilai $LT_{95}$ bagi kelima-lima umpan racun berbeza sedikit: fipronil = indoxacarb > abamectin > hydromethylnon > imidacloprid. Tambahan pula, keputusan yang diperoleh menunjukkan nimfa lipas lebih rintang terhadap racun umpan berbanding dengan lipas dewasa. Dari segi transmisi sekunder, keberkesanan umpan racun dipengaruh oleh kehadiran makanan pilihan yang lain ($p = 0.05$). Ini adalah, kerana nilai $LT_{50}$ dan $LT_{95}$ yang diperoleh adalan lebih tinggi dalam keadaan yang diberikan makanan bersama dengan bangkai berbanding dengan hanya diberi bangkai sahaja. ($p < 0.05$). Kajian dijalankan mengguna umpan racun fipronil dan indoxacarb. Respon pemakanan lipas jantan dewasa, lipas betina dewasa, lipas betina yang bertelur, nimfa awal, nimfa pertengahan dan nimfa lewat telah dikaji. Kedua-dua umpan racun tersebut tidak menunjukkan sebarang perbezaan yang signifikan ($p > 0.05$) dari segi kadar memakan dan masa memakan yang diperuntukkan ke atas umpan racun. Masa yang diambil oleh lipas untuk mendekati kedua-dua umpan racun dan untuk mati selepas memakan umpan racun juga dikaji. Respon awal lipas terhadap umpan racun dan kesan ketosikannya dipengaruhi secara signifikan ($p < 0.05$) oleh hubungan tiga faktor utama: jenis umpan racun, bilangan umpan racun yang diberikan dan tahap kelaparan yang berlainan. Semakin banyak bilangan umpan racun diguna, semakin cepat lipas Jerman respon terhadap racun tersebut ($p < 0.05$). Lipas Jerman bertindak dengan cepat terhadap Maxforce Select® gel bait = Maxforce FC® gel bait > Avert® gel bait = Infiniti® gel bait = Advion® gel bait. Kesan membunuh daripada kelima-lima umpan racun ini dari yang paling berkesan sehingga yang kurang berkesan adalah: Maxforce select® (230.76 ± 3.57 minit) < Advion® (323.21 ± 4.00 minit) < Maxforce FC® (479.65 ± 9.25 minit) < Avert® (540.39 ± 7.11 minit) < Infinit® (2084.73 ± 23.71 minit). Apabila ditingkatkan kelaparan, lipas German bertindakan untuk mendapatkan umpan racun yang diberi ( $p < 0.05$) dan juga kadar membunuhnya.

# BEHAVIORAL AND TOXICOLOGICAL RESPONSES OF THE GERMAN COCKROACH, *BLATTELLA GERMANICA* (L.) (DICTYOPTERA: BLATTELLIDAE), TOWARDS TOXIC BAITS

## ABSTRACT

This study focuses on the comparative performance of selected insecticide gel baits and the association between the feeding behaviour of German cockroaches, *Blattella germanica* (L.), and the toxicity of the baits. An arena test was conducted to evaluate the effectiveness of gel baits on three life stages of the German cockroach: adult males, adult females, and intermediate nymphs. A total of five commercial gel baits were tested and their effectiveness was evaluated by comparing their $LT_{50}$ and $LT_{95}$ values. The sequence of effectiveness of the baits from the least to greatest $LT_{50}$ value ($p = 0.05$) was: fipronil = indoxacarb > imidacloprid > abamectin > hydramethylnon. However, the $LT_{95}$ values were slightly different: fipronil = indoxacarb > abamectin > hydromethylnon > imidacloprid. In addition, nymphs were less vulnerable than adults. In terms of secondary transmission, the performance of the five gel baits were absolutely affected by the presence of an alternative food ($p = 0.05$) because the $LT_{50}$ and $LT_{95}$ value without an alternative food were significantly lower ($p < 0.05$) than when an alternative food source was present along with the carcasses.. Further studies were conducted using fipronil and indoxacarb gel baits. The feeding response of adult males, adult non-gravid females, gravid females, late nymphs, intermediate nymphs, and early nymphs were studied. The two types of bait did not differ significantly ($p > 0.05$) in terms of feeding frequency and the amount of time that German cockroaches spent on the baits. The time taken for cockroaches to approach the gel bait and the time required for them to die after consuming the gel bait were also evaluated in this study. The initial response of the cockroaches to the baits and the killing effect of the baits were significantly ($p < 0.05$) affected by the association of the three main factors: types of gel bait, the number of baits placed, and differences in starvation level. When greater numbers of baits were used, German cockroaches were more likely to approach it ($p < 0.05$). German cockroaches reacted rapidly towards Maxforce Select® gel bait = Maxforce FC® gel bait > Avert® gel bait = Infiniti® gel bait = Advion® gel bait. In addition, the killing effects (i.e., time required to cause death) of these five insecticide gel baits from most effective to least effective were: Maxforce Select® (230.76 ± 3.57 minutes) < Advion® (323.21 ± 4.00 minutes) < Maxforce FC® (479.65 ± 9.25 minutes) < Avert® (540.39 ± 7.11 minutes) < Infinit® (2084.73 ± 23.71 minutes). An increase in the level of starvation of the German cockroach, fastened the time taken for cockroaches to access the baits ($p < 0.05$) and also enhanced its killing effect on German cockroaches ($p < 0.05$).

# CHAPTER ONE

# GENERAL INTRODUCTION

The high reproductive potential (Rehn, 1945), great adaptability to human dwellings, ability to withstand temporary adverse conditions, and ease of dispersal have made cockroaches, particularly the German cockroach, *Blattella germanica* (Linnaeus), the most important urban insect pest in many parts of the world. With the increase in cockroach problems in urban environments due to increasing population size, the demand for pest control is growing dramatically.

In an expending pest control market, numerous strategies and technologies are available to combat the domiciliary cockroach population. These efforts rely heavily on the application of insecticides, especially spray formulations. However, with the increase in the frequency of insecticide applications has increased cockroach resistance towards various types of insecticides.

Nowadays, concerns of consumers, pest control professionals, and regulatory authorities about indoor pesticide use have prompted a demand for risk-reducing strategies to control cockroaches. Therefore, cockroach baits have become widely used in the pest control market due to their effectiveness and environmental safety compared to conventional insecticides.

However, the use of baits is not full proof. German cockroach infestations occur in highly heterogeneous environments, where the populations are aggregated in scattered foci. Complicated foraging patterns and feeding behaviours of each group and variations in the reproductive stages present may limit the performance of baits. The efficacy of baits also is determined by the mode of action of their active ingredients, the type of food base and odorant used, and the design of the bait containers (Nalyanya and Schal, 2001).

Understanding of cockroach feeding behaviours and foraging patterns is vital to the effective and efficient control of cockroaches. The relationship between baits and the response of cockroaches to them needs to be studied. Therefore, in this study the lethal dosages for different genders and stages of cockroaches is verified, an optimum amount of bait consumption is determined, and the intimate association between bait intake and starvation level of German cockroaches are examined. To examine these parameters, the following objectives are addressed:

1. To establish the $LT_{50}$ and $LT_{95}$ of selected commercial insecticide gel baits against starved and unstarved German cockroaches under laboratory conditions.
2. To evaluate the effects of secondary transmission on the insecticides susceptibility against German cockroach.
3. To elucidate the effects of several factors (nymphal development, genders, presence of alternative food) on the feeding response of German cockroaches towards fibronil and indoxacarb gel bait.
4. To compare the effects of the selected parameters (the number of baits placed, the difference in starvation level, and the type of gel baits) on the time it takes for cockroaches to approach the bait and die.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Medical and economic importance of cockroaches

Cockroaches rank with termites as the most important insects that must be dealt with by pest control operators. In Malaysia, cockroaches are considered to be the second most dominant insect pest after mosquitoes (Yap and Foo, 1984; Lee et al., 1999). One survey showed that the cockroach control business commands a 20% market share in the local pest control industry (Lee and Yap, 2003). The most predominant domiciliary pest cockroaches in Malaysia (and in the world) are the German cockroach, *Blattella germanica* (Linnaeus), and the American cockroach, *Periplaneta americana*.

German cockroaches are usually found indoors and normally disperse throughout food preparation areas. They commonly are found in hotels and restaurants (Yap et al., 1991; Lee at al., 1993; Robinson, 2000; Lee and Robinson, 2001). For household infestation, low-income housing areas normally are the target for German cockroaches due to poor sanitation (Miller and Meek, 2004). American cockroaches are considered to be predomestic because they are not common within houses. However, they can move indoors and live in human structures (Oothuman et al., 1984; Yap et al., 1991; Lee at al., 1993). Both species have a truly cosmopolitan distribution because they live in close associated with man in his domestic environment (Princis, 1969).

Cockroaches are a nuisance. They produce an unpleasant odourous secretion that ruins the flavour of food and the environment. The behaviour of regurgitating and defecating while feeding on food and while resting on utensils makes them a food and utensil contamination pest (Lee, 1997). Due to their movement from unsanitary places into our homes or onto foods, they also are pathogen carriers.

Cockroaches are mechanical vectors because most of the pathogenic bacteria and viruses they harbour are located on the outside of their body. They passively cause disease by leaving behind pathogenic organisms on the food that they contact. Cockroaches are capable of carrying or transmitting various types of gastro-intestinal related pathogens

(Frishman and Alcamo, 1977; Alcamo and Frishman, 1980), such as *Slamonella* bacteria (Rueger and Olson, 1969; Stek et al., 1979; Rampal et al., 1983), *Clostridium* sp. (Cornwell and Mendes, 1981), *Bacillus* sp. (Wedberg et al., 1949; Brenner, 1995), and *Escherichia* sp. (Burgess and Chetwyn, 1979). In Malaysia, various pathogenic organisms have been isolated from field collected cockroaches (Rampal et al., 1983; Oothuman et al., 1989).

Other species of bacteria, protozoans, and viruses also have been isolated, such as those associated with leprosy (Arizumi, 1934a; 1934b; Moiser, 1945), pneumonia (Burgess and Chetwyn, 1979; Rivault et al., 1993a; 1993b), plaque (Hunter, 1906; Jettmar, 1935), amebiasis (Schneider and Shields, 1947), dysentery (Burgess, 1982; Oothuman et al., 1989), and paralytic polio (Syverton et al., 1952; Dow, 1995). Pathogenic or toxin-producing bacterial species such as *Aspergillus*, *Cladosporium*, and *Penicilium* have been isolated from *B. germanica* (Fuchs, 1976), and *P. americana* has been found to harbour helminthes such as *Moniformis* sp. (Anuar and Paran, 1976; Oothuman et al., 1985) and *Thelastoma* sp. (Anuar, 1987).

The most significant health risk associated with cockroach infestation is the production of allergens (Brenner et al., 1991). Inhalation of accumulated cockroach allergens, such as their body extracts, exuvia, and frass, can cause serious health problems, such as allergies (Brenner et al., 1991), dermatitis (Bernton et al., 1972), and eczema and asthma (Schulaner, 1970; Kang et al., 1979; Kang and Chang, 1985). According to Pope et al. (1990), the victims of these ailments often are the elderly or young children because they are more sensitive to bronchial contaminates.

Cockroaches may also bite humans (Brenner et al., 1987; Koehler et al., 1990; Brenner, 1995). A burning sensation, dizziness, and vomiting can occur after contact with defensive cockroach secretions (Roth and Alsop, 1978). Anxiety combined with the stigma related to infestation reportedly can create an irrational mental disorder to homeowners who particularly loathe these creatures (Schrut and Waldron, 1963).

## 2.2 *Blattella germanica* (Linnaeus) – the German cockroach

### 2.2.1 Introduction

The German cockroach is also known as the “steam fly” in England, whereas the Americans call it the “croton bug”. The German cockroach has a worldwide distribution and is the most prevalent cockroach species in and around homes, apartments, supermarkets, food processing plants, and restaurants. Additionally, cruise ships and naval vessels can also be heavily infested (Koehler at al., 1990)

### 2.2.2 History

Historically, scientists believed that German cockroaches originated from North East Africa between the great African lakes, Ethiopia, and the Republic of the Sudan. Many centuries ago, this insect found its way into Eastern Europe on Greek and Phoenician ships, spreading into Byzantium, Asia Minor, the Black Sea region, and southern Russia. It then slowly spread northward and westward across Europe. Once the German cockroach was introduced into Western Europe it was distributed via commerce and human movement to virtually all parts of the world. The German cockroach was established in England as recently as the middle of the 1900s. According to Miall and Le Patourel (1989), its supposed establishment in Leeds was by means of breadbaskets carried by soldiers returning from the Crimean War (1854–1856). *Blattella germanica* was first named *Blatta germanica* by Linnaeaus in 1767 for insects collected from Denmark.

### 2.2.3 Habitat

German cockroaches prefer a warm and moist environment. Therefore, it has become a common pest in kitchens and restaurants where food, warmth, and moisture provide the necessary ecological requirements (Cornwell, 1968). However, German cockroaches have also been found outdoors in many parts of the world (Shuyler, 1956; Cornwell, 1968).

### 2.2.4 Morphology

*Blattella germanica* is a small cockroach. The adults are 10–14 mm in length and yellowish-brown in colour, with two dark parallel bands on the pronotum (Guthrie and Tindall, 1968; Lee and Robinson, 2001). Adult males have a slender body, tapering abdomen, and a pair of styli on the subgenital plate. Females are more robust, have a rounded abdomen, and lack styli on the subgenital plate (Appel, 1995).

### 2.2.5 Biology

The German cockroach undergoes incomplete metamorphosis with three life stages: egg, nymph, and adult. The life cycle begins with fertilization of the egg followed by a series of molts in the nymphal stage and ends with the emergence of a fully winged adult at the final molt. The life cycle is completed in 100 days under favorable conditions (Archbold et al., 1987).

The nymphal stage begins when the first instar hatches from the ootheca. Normally the number of molts is either five or six in males (Seamans and Woodruff, 1939; Roth and Stay, 1962) and six in females (Tanaka and Hasegawa, 1979; Keil, 1981). According to Tanaka (1981), the number of molts is determined by the 3rd late instar. Nymphs with relatively small bodies undergo six molts and those with larger body undergo five molts. Kunkel (1975) reported that each molt takes 20 minutes at 29 °C. The period for complete development of nymphs is around 50–60 days at room temperature. Sex can be identified during the early stage of the nymph (Ross and Cochran, 1960).

The adults are fully winged and have developed sexual organs. Males begin to mate within three days after emergence the final molt (Roth and Willis, 1952). Females begin to mate at 4–5 days (Roth and Willis, 1952; Ueda et al., 1969) or at 6–7 days after emergence (Tanaka, 1973). Before mating, sex recognition occurs via contact of the antennae of both sexes. Courtship begins when the females release a volatile pheromone to attract males. Once in contact with the female the male raises its wings, exposing its dorsal gland, towards which the female can advance to obtain a sugary secretion (Nojima et al., 2002). Mouthing usually leads to mating, but this is not always the case (Gadot et al., 1989). One mating may

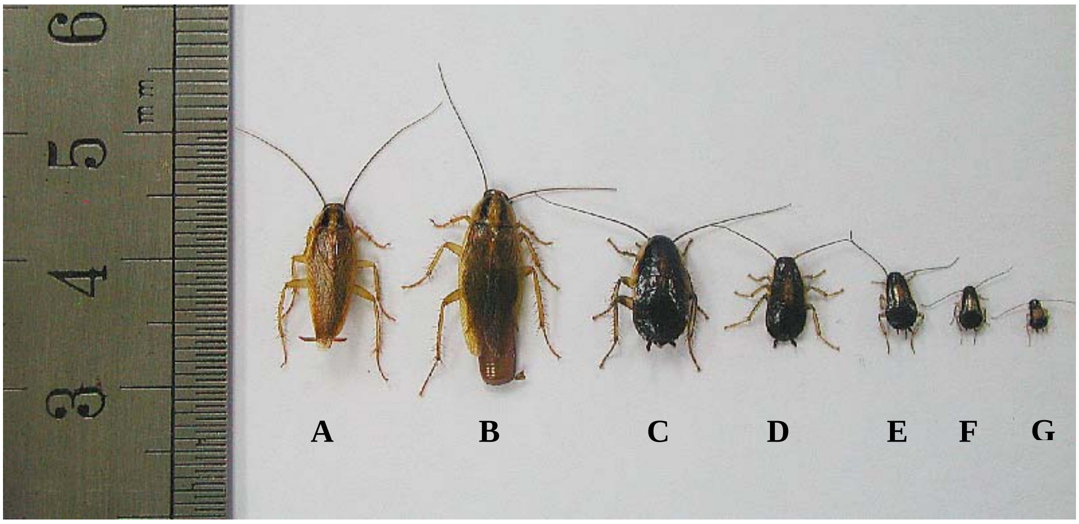

Plate 2.1: Morphological view of the German cockroach. A: Male German cockroach. B: Gravid female German cockroach. C : Late nymph. D and E: Intermediate nymph. F: Early nymph

be sufficient to fertilize all of the eggs produced during the lifetime of a female, but repeated copulation by females sometimes occurs (Rau, 1945). However, eggs do not always hatch due to changes in temperature (Tsuji and Mizuno, 1972, 1973), the reduction of viable embryos due to lethal doses of chemicals (Keil and Ross, 1977), the premature drop of ootheca caused by exposure to insecticides (Barson and Renn, 1983), and fungal infections (Archbold et al., 1987). Virgin females must mate within an average of 14 days after emergence or else an unfertilized egg case will be formed (Roth, 1970). All oothecae formed by virgin females are unfertilized (Roth and Stay, 1962). However, unmated females continue to form new ootheca (Roth and Willis, 1952). Gravid females will carry their ootheca until it hatches (Metcalf and Metcalf, 1993). Females always live longer than males.

## 2.3 The behaviours of cockroaches

"*New and improved control methods can be developed by understanding the natural behaviour patterns of the cockroach.*" – Roland Metzger (1995)

### 2.3.1 Aggregation behaviour

Aggregation behaviour is important in the spatial distribution of German cockroaches. The aggregation pheromone plays an important role in this behaviour. The cockroach aggregation pheromone functions primarily as an attractant and secondarily as an arrestant (Burk and Bell, 1972; Sakuma and Fukami 1990, 1993), thus attracting cockroaches to a particular area and arresting their movements once tactile contact is made with the pheromone source (Sakuma and Fukami 1993). The aggregation pheromone is attractive to both sexes and all stages of instars (Ishii and Kuwahara, 1968), and it is not strictly species specific (Appel, 1995). Aggregation behaviour of cockroaches influences the hatching of nymphs. For example, aggregation of gravid females within a group helps ensure that nymphs hatch under favorable conditions (Bret and Ross, 1983). Pettit (1940) observed that German cockroach nymphs developed more slowly when isolated. Physical contact and aggregation contributes to the accelerated growth rates of cockroaches (Rust and Appel, 1985).

The attractant activity of the aggregation pheromone was first documented in German cockroach fecal material by Ishii and Kuwahara (1967). Fecal material is covered by peritrophic membranes that are secreted around the food in the digestive system. After being exposed to air and room temperature, fecal material is active and can lead to aggregation for a year or longer. The tendency to form aggregations is more pronounced at a higher population density (Ishii and Kuwahara, 1967, 1968).

### 2.3.2. Feeding behaviour

Food is an important extrinsic factor that controls moulting and reproduction in *B. germanica* colonies. Depletion of the food source may cause delays in the initiation of another moulting cycle or in the female reproductive cycle because feeding may control moulting in cockroaches via the central nervous system and the stretch receptor (Kunkel, 1966).

Feeding frequency and duration differ according to sex and reproductive condition (Silverman, 1986). Males and non-gravid females feed and drink more often than gravid females. Silverman also found that the average duration of each feeding event was lowest for gravid females and the duration of each drinking event was lowest for males.

Cochran (1983) showed that feeding and drinking in the adult female German cockroach peaked during the egg maturation period but were abruptly terminated in the presence of an egg case. Females have to feed more before forming an ootheca (Kunkel, 1966) because the food consumed must contain enough protein to be converted into egg yolk (Hamilton and Schal, 1988). DeMark and Bennett (1994) found that both nymphal stages (males and females) were very active and had relatively high consumption rates in the first half of the stadia, whereas the second half of the stadia was characterized by low activity and low food consumption.

Variation in feeding activity within most cockroach species is common. Rollo and Gunderman (1984) noted variation in the day–to-day feeding of the American cockroach and found that the duration of starvation as well as the physiological (gonotrophic) age of the females contributed to this variation.

### 2.3.3 Foraging behaviour

The efficiency with which an individual forages for resources such as food, water, harbourage, and mates is critical for its survival, growth, development, and reproductive potential (Bell, 1991). Foraging efficiency may be a consequence of gender, maturation of sensory organs, experience, or all three (DeMark et al., 1993).

Foraging activities of *B. germanica* are related to the circadian activity phases (Metzger, 1995). Generally, the peak time of foraging was found to coincide with the peaks of locomotory activities (Hocking, 1958). The activities peak at 3 hours before scotophase and 1 hour before photophase (Fuchs and Sann, 1981). This active locomotion coincided with mate-searching activities and high food demand for the formation of the ootheca. However, gravid females showed significantly less locomotory activity, but did resume a diel rhythm of locomotion. Virgin females with high locomotory activity showed a daily pattern similar to that of mated females.

Distance is one of the factors that influences the foraging activities in animals (Stephen and Krebs, 1986). A more discernible foraging rhythm can be observed when food and water are placed far from their refuge. The shorter the distance between shelters and food sources, the higher the probability the food sources will be rapidly found and exploited (Rivault and Cloarec, 1991).

Foraging behaviour also may be influenced by population density. Ebeling and Reierson (1970) reported that cockroach activity is inversely related to population density. Males drink more often at lower population densities. The effect of sex and stage of reproduction on food and water intake is noticeable. Gravid females are able to survive without water for up to 5 days and can go without food for an even longer period of time (Metzger, 1995). Males have greater drinking activities than females because the rate of water loss in males is three times higher than in females (Appel et al., 1983).

Cockroaches are able to learn the position of their shelter, a hidden target, or stable food sources in relation to visual landmarks (Durier and Rivault, 2000) and they are able to return to the food sources. Cockroaches are excellent learners and they can retain information for days (Hunter, 1932; Ebeling et al., 1966; Alloway, 1972).

### 2.3.4 Exploratory behaviour

Exploitation of food resources is a fundamental condition for the survival of all insects. Before an insect makes a decision to ingest food, the level of risks, the availability of food, the place to forage, and the types of food to ingest must be assessed (Begon et al., 1986). Hungry cockroaches will exit their hiding places, sample the air, and then move steadily towards the food source, ignoring all visual cues (McCoy, 1998).

German cockroaches exhibit exploratory behaviour once they leave an area, whereby their antennae will make contact with a vertical surface. Exploratory behaviour is not linked to the discernible time of day or to the activation of certain physiological cycles. This behaviour facilitates learning and recognition of specific topographic information, which provide an advantage for foraging or retreating to harbourage (Metzger, 1995). The level of exploratory behaviour is related to the amount of locomotory activity of each life stage. For example, 25% of males have a running activity that is 3–4 times higher than that of other stages. Exploratory behaviour depends on exogenous and endogenous factors.

The level of activity can be reduced by satiation (Darchen 1952, 1954 in Smith and Appel, 2008) and by whether or not the immediate environment has been explored. An increase in light intensity and temperature can contribute to an increase in exploratory behaviour. However, neither decreased light intensity nor the angles of inclination of the walking surface have a measurable effect on exploration. Ebeling and Reierson (1970) reported that the population density is negatively related to exploratory activities. Akers and Robinson (1983) showed that the level of exploratory behaviour of cockroaches in the field was higher in terms of movement and exploitation than that of laboratory-reared cockroaches.

### 2.3.5 Food stealing behaviour

When food becomes scarce, food stealing can be observed in German cockroach populations (Rivault and Cloarec, 1990). Food stealing occurs when there is an important retardation between the moment a forager discovers food and the moment it is consumed. Kleptoparasitism describes the interspecific (Rothschild and Clay, 1952) and intraspecific (Brockmann and Barnard, 1979; Barnard and Sibly, 1981) stealing of food.

The food stealing behaviour of the German cockroach was first reported by Rivault and Cloarec (1990). This behaviour appeared towards the end of the exploitation of the food source. The occurrence of this phenomenon was related to the structure and the quality of food. Normally, food stealing behaviour occured when cockroaches found food that could be easily broken into small pieces and carried to another place. However, this rarely occured in the natural environment. Furthermore, the probability of food stealing decreased as the distance from shelter increased. This behaviour appeared when competition for food among cockroaches increased (Rivault and Cloarec, 1990).

Transportation of stolen pieces reflects the selfish behaviour of cockroaches. According to Barnard and Sibly (1981), some animals try to monopolize a food source by removing it to avoid conspecifics. Kleptoparasitic behaviour leads to benefits for the dominant animal (Brockmann and Barnard, 1979). Rivault and Cloarec (1990) observed that larger cockroaches (adults and larger nymphs) were always the dominant ones and benefited from monopolizing stolen pieces of food. This is due to the fact that adults and large nymphs require more energy. However, smaller nymphs appeared to be tolerated by the adults and larger nymphs around a food source under an unfavorable circumstance.

### 2.3.6 Rhythmic behaviour

The daily rhythm contains two phases of high activity: the first occurs at the onset of scotophase from 1400 hours to a peak at 1700 hours, whereas the second takes place shortly before the photophase between 2200 and 2300 hours. Each cockroach stage demonstrates different levels of circadian rhythm. Males are the most active and exhibit the higher main peak of activity. Gravid females have a distinctive circadian rhythm of movement compared to other stages because their movements are suppressed when the ootheca develops. Their activity decreases to a minimum and no significant differences between the light and dark photoperiod have been observed. However, the daily activity rhythm of gravid females can be reactivated by thirst and hunger (Sommer, 1975). Sommer (1975) reported that nymphs do not exhibit a pronounced daily rhythm when exposed to artificial light, but Danzer et al. (1988) found that nymphs displayed a stable daily rhythm.

## 2.4 Chemical control

### 2.4.1 Introduction

Chemical control is the most commonly used method to deal with cockroaches in public health and household insect pest control (Yap et al., 2003). The chemicals used are mainly neurotoxic insecticides (Lee and Lee, 2004). The application of these chemicals indirectly affects other non-target urban pest such as ants, carpet beetles, silverfish, and stored-product pests (Landau et al., 1999; Robinson, 2001). The decline in the status of the German cockroach as the major pest is due to the combination of various control measures, including improvements in building construction, crack and crevice treatment, and baiting (Robinson, 1999).

### 2.4.2 The efficacy of baiting

Until recently, the control of cockroaches (Blattaria) largely relied on synthetic insecticide sprays. Application of residual insecticide has been the primary method of cockroaches control in public housing for the past 50 years (Byne and Carpenter, 1986). However, this method has caused public concern about insecticide resistance and the health risks associated with pesticide use (Cooper, 1999). With the development of gel baits, which can be selectively applied where cockroaches are present, this situation has changed (Pospischil et al., 1999).

Bait is a mixture of insecticide and an attractive food substance (Reierson and Rust, 1996). The advantages of baits compared with other methods of control are widely acknowledged. Use of bait for cockroach control does not affect human safety because of the discrete and containerized placement of chemicals. Other advantages include increased intrinsic activity of the ingested active ingredient, no interaction between residues and surfaces, the combination of chemicals with attractants or arrestants, and easy removal and replacement (Reierson and Rust, 1984).

For the control of cockroach infestations, gel baits have gained more importance compared with conventional sprays. Baits are particularly suitable for use in sensitive environments, such as food preparation areas, hospitals, and kindergartens (Benson and Zungoli, 1997). Because baits can be placed in bait stations, insecticides that stain can be applied indoors without concern (Koehler et al., 1991). Moreover, baits have long-lasting activity and are odorless (Cornwell, 1976). The use of baits also results in less environmental contamination and greater ease of application for homeowners (Rust, 1986).

However, baits have some disadvantages. For example, they have a limited sphere of activity for discrete stations and critical placement is necessary for optimal results. Most insecticides are repellents when used in baits, and long-lasting sublethal baits may contribute to resistance problems (Reierson and Rust, 1984). Since baits rely on the target pest to visit and feed on the toxicant, customers might believe that baits produce slower results. This will pose a problem in certain places, such as hotels and restaurants, where rapid elimination of the pest in question is usually required. In these situations, the integration of non-residual, rapid-acting space or surface spray in combination with bait application may be an option (Lucas and Invest, 1993). Baits must also compete with other food sources, so correct placement often is critical. Furthermore, cockroaches rarely travel extensive distances for food and water if those resources are available nearby. For baiting to be successful, however, a high proportion of the population must feed on the bait (Lucas and Invest, 1993).

## 2.5 Commercial baits

### 2.5.1 Slow-acting insecticides

#### 2.5.1.a Abamectin

Abamectin is a macrocyclic lactone product derived from the soil microorganism *Streptomyces avermitilis*. It is a mixture of 80% avermectin $B_{1a}$ and 20% avermectin $B_{1b}$ (Figure 2.1). Like most other insecticides, avermectins are nerve poisons. They stimulate the gamma-aminobutyric acid (GABA) system, a chemical "transmitter" produced at nerve endings, which inhibits both nerve and nerve-to-muscle communication.

Abamectin is effective as a stomach poison against a broad spectrum of insect species such as ants (Glancey et al., 1982), cloth moth (Bry, 1989), lice (Barth and Preston, 1985), flies (Miller et al., 1986), termites (Su et al., 1987), and yellow jackets (Chang, 1988). It was registered in the United States for cockroach control in 1990 (Wright et al., 1992). Abamectin cockroach bait (Avert, Whitmire Research Laboratories, St. Louis, Mo., USA) is a slow-acting toxicant suitable for controlling populations of German cockroach (Koehler et al., 1991). Ballard and Gold (1983) showed that abamectin effectively kills German cockroaches when ingested.

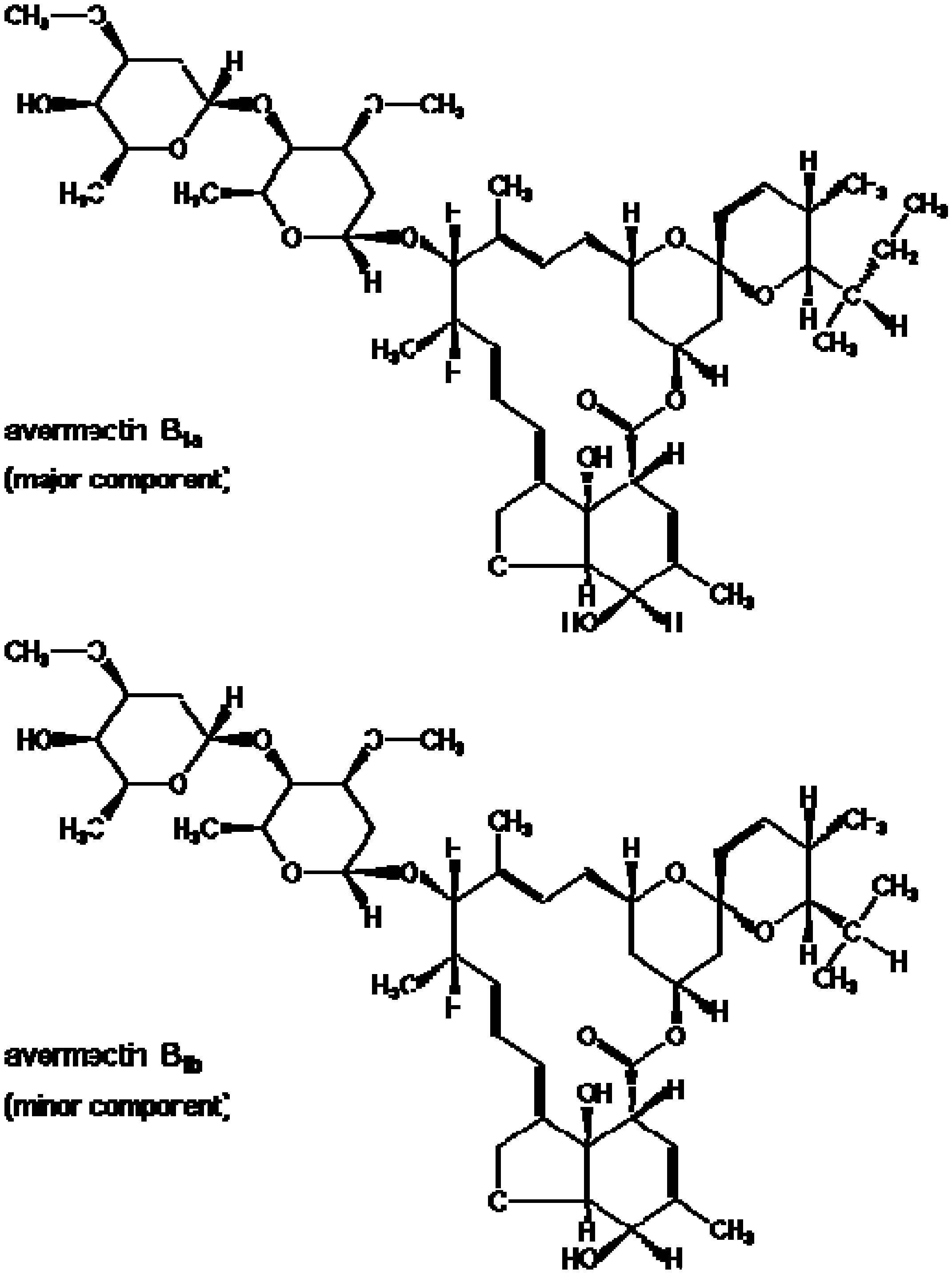

Figure 2.1: Chemical structure of abamectin (avermectin $B_{1a}$ and $B_{1b}$)

The affected insects become paralyzed, stop feeding, and die after a few days. Cochran (1985) demonstrated that higher amounts of abamectin in the diet were required to cause mortality. However, lower concentrations inhibited mating and reproduction. Low concentrations of abamectin also caused failure of leg muscles of American cockroach to respond to stimuli (Tanaka and Matsumura, 1985). Cochran (1985) reported that newly emerged adult female German cockroaches exhibited high mortality after feeding on abamectin bait and that survivors failed to reproduce. Abamectin also is effective in controlling the Oriental cockroach, *Blatta orientalis* (L.); brown-banded cockroach, *Supella longipalpa* (Serville); American cockroach, *P. ameicana* (L.); Australian cockroach, *P. australasiae* (F.); brown cockroaches, *P. brunnea* (Burmeister), and smoky brown cockroaches, *P. fuliginosa* (Serville) (Koehler et al., 1991). In addition, abamectin is effective against insecticide-resistant cockroaches (Cochran, 1985). Avert® is available to pest control operators in the form of fine dusts or pressurized gel. The powder formulation of Avert has been shown to be effective in controlling German cockroaches in laboratory and field tests (Appel and Benson, 1995).

#### 2.5.1.b Hydramethylnon

Hydramethylnon [tetrahydro-5,5-dimethyl-2(1H)-pyrimidinone(3-[4 (trifluoromethyl) phenyl]-1-(2-[4-trifluomethyl)phenyl]ethenyl)-2-propeny-lidene) hydrazone] or amidino-hydrazone (Figure 2.2) was first discovered in 1979 by J.B. Lovell (in Silverman and Shapas, 1986). It inhibits mitochondrial respiration and has been formulated in baits called COMBAT Roach Control System MAXFORCE (American Cyanamid, Clifton, NJ, USA) for use against indoor cockroach populations (Appel, 1990). It was introduced to Malaysia in the 1990s (Khadir and Lee, 1995). Hydramethylnon is most effective against insects when it is formulated as a stomach poison or bait (Hollingshaus, 1987). It affects the cell's ability to convert food into energy. The result is that the insects consume the chemical, slowly run out of energy, become weak, and die (Garfield, 1990).

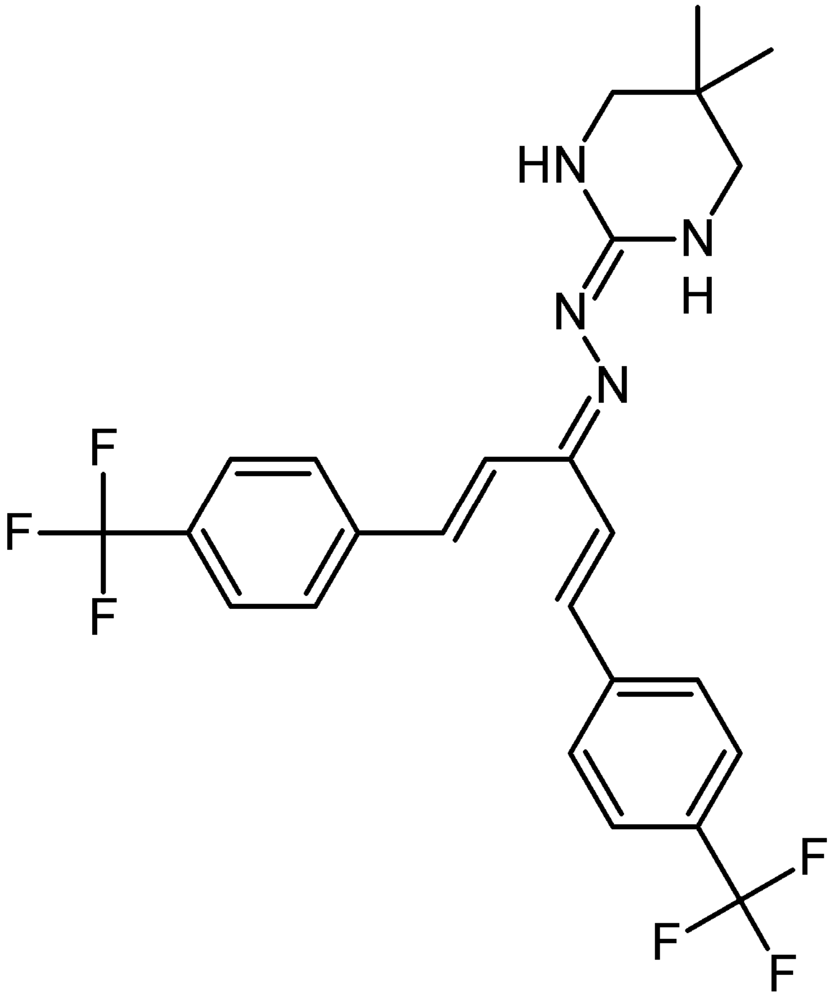

Figure 2.2: Chemical structure of hydramethylnon

This chemical has a delayed action; symptoms of intoxication generally occur within 24 hours after exposure (Silverman and Shapas, 1986).

Such delayed action is useful for controlling ants and termites because it permits toxicant transfer among colony members (Su et al., 1982). Hence, the delayed action of hydramethylnon enables the transmission of the toxicant through coprophagy (ingestion of faeces; Silverman et al., 1991) and necrophagy (consumption of dead bait-fed cockroaches; Gahlhoff et al., 1999) among the cockroaches. Milio et al. (1986) and Hollingshaus (1987) proved that this insecticide was very effective against German cockroaches. Hydramethylnon blocks site II (succinate-coenzyme Q reductase) of the electron transport chain, which prevents ATP production from reduced pyridine nucleotides generated in the citric acid cycle (Hollingshaus, 1987).

In 1991, Koehler and Patterson found that a Jacksonville cockroach strain, which was collected from low-income apartments in Jacksonville, FL, USA, in 1988, showed low-level resistance at a bait concentration of > 1.0% hydramethylnon due to avoidance of the treated bait. Furthermore, Silverman and Beiman (1993) described a strain of German cockroach (T-164) that exhibited avoidance behaviour toward an earlier version of the Maxforce bait formulation (Clorox Company, Oakland, CA, USA) that contained hydramethylnon due to aversion to D-glucose in the Maxforce bait matrix. According to Valles and Brenner (1999), the intensive use of hydramethylnon in various bait formulations for ~15 years against the German cockroach caused minimal development of physiological resistance. However, cross-resistance among pyrethroid, carbamate, and organophophate insecticides in German cockroach does not occur.

### 2.5.2 Fast acting insecticides

#### 2.5.2.a Fipronil

Fipronil is an outstanding new insecticide with good selectivity between insects and mammals. The insecticidal properties of fipronil [(+)-5-amina-1-(2,6-dichloro-a,a,a–trifluoro-p-tolyl)-4-triflouromethyl-sulfinylpyrazola-3 carbonitrile] were discovered by

Rhone-Poulenc Agro in 1987 at Ongar, UK (Colliot et al., 1993) (Figure 2.3). It is classified in the phenylpyrazole class of insecticide. Phenylpyrazole insecticides are neurotoxic, and they block the transmission of signals by inhibiting the neurotransmitter gamma-aminobutyric acid (GABA) (Colliot et al., 1992; Cole et al., 1993, Moffat, 1993). This new class of pesticides exhibits both herbicidal and insectidal characteristics (Klis et al., 1991).

Fipronil is highly effective at a low dosage against both piercing-sucking and chewing agricultural insect pests, and it can be delivered via soil, foliar, bait, or seed treatment applications (Colliot et al., 1992; My, 1994). It acts as both a contact and a stomach poison. The insecticidal action involves blocking the GABA-gated chloride channel (Hainzl and Casida, 1996). This causes hyperexcitation of the nerves and muscle of contaminated insects. Fipronil contains a triflupromethylsufiny substituent that is a highly active, broad-spectrum insecticide from the phenyl pyrazole family (Hainzl and Casida, 1996). In 1999, fipronil was made available in bait formulations for use against German cockroaches (Holbrook et al., 2003). It was used by Bayer to create MAXFORCE bait stations that offer-long term control of cockroaches and ants. Kaakeh et al. (1997) confirmed that fipronil was very effective in nanogram quantities against laboratory-reared German cockroaches.

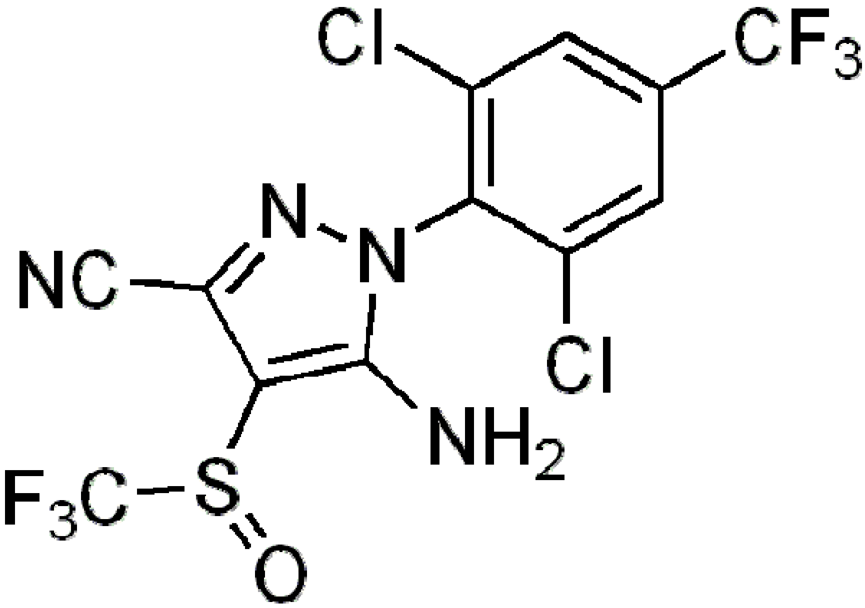

Figure 2.3: Chemical structure of fipronil

### 2.5.2.b Imidacloprid

Imidacloprid {1-[(6-chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine} (Figure 2.4) is a neonicotinoid insecticide. It is a chloronicotinyl compound with low soil persistence, high insecticidal potency, and relatively low mammalian toxicity (Nauen, 1995). Imidacloprid is a systemic insecticide that is chemically related to the tobacco toxin nicotine. Like nicotine, it acts on the nervous system. Worldwide, it is considered to be one of the insecticides used in the largest amount (Cox, 2001). Its use as a new crop protection agent was first proposed in 1991 (Elbert et al., 1991; Leicht, 1993). Imidacloprid exhibits good oral and contact efficacy against cockroaches, and it can be formulated as gel baits to meet the demand for a more effective and safer method for controlling cockroaches (Pospischil et al., 1999). Imidacloprid is selectively toxic to insects mainly because the structural differences between the insect and vertebrate nAcChR results in its higher affinity for the insect neural receptors (Tomizawa et al., 2003). Pospischil et al. (1999) reported that imidacloprid cockroach gel bait showed outstanding activity even 27 months after the application of the gel under various conditions. Extensive laboratory and field trials and initial market feedback demonstrated the high efficacy of imidacloprid against all economically important cockroach species (Pospischil et al., 1999). Furthermore, it also is effective against other insects, such as ants, wood lice, and crickets.

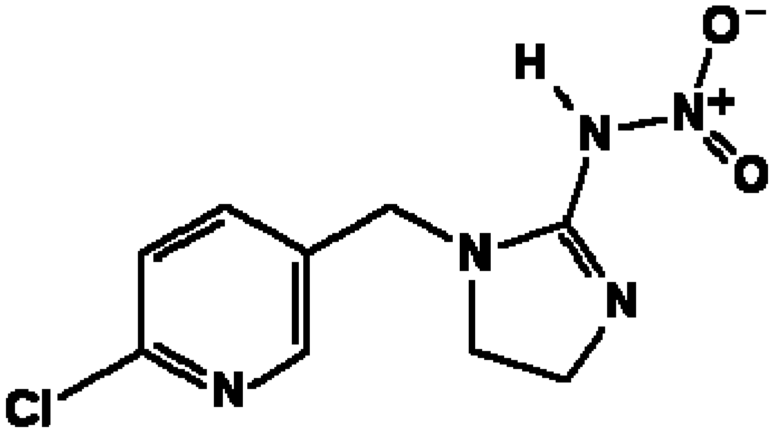

Figure 2.4: Chemical structure of imidacloprid

### 2.5.2c Indoxacarb

Indoxacarb, or methyl(S)-7-chloro-2,3,4a,5-tetrahydro2-[nethoxycarbonyl (4-trifluoromethoxyphenyl) carbamoyl]indeno[1,2e][1,3,4] oxadiazine-4a-carboxylate (Figure 2.5), is a neurotoxic oxadiazine insecticide discovered by E.I. DuPont and Co (McCann et al., 2001). It is the first commercialized pyrazoline-type insecticide against insect strains that had developed resistance to organophosphates, carbamates, and pyrethroids (McCann et al., 2001). Indoxacarb is a 75% S: 25% R mixture of enantiomers at the chiral bicyclic carbon; DPX-JW062 is the corresponding recemic compound (Wing et al., 2000). The discovery of indoxacarb (DPX-MP062) was achieved by an extensive effort to optimize pyrazoline-type chemistry towards high insecticidal activity, low toxicity in non-target organisms, and safety in the environment (Zhao et al., 2003).

Indoxacarb must be bioactivated by the insects into the active decarbomethoxylated metabolite (Wing et al., 1998 in Appel, 2003). It does not cause cross-resistance to carbamates, pyrethroids, spinosads, cyclodienes, benzoylureas, or organophosphate (Zhao et al., 2002; Wing et al., 2005). The metabolite then poisons the insect sodium channels by a voltage-dependent block, leading to a decrease in overall nerve firing (Wing et al., 1998 in Appel, 2003). Indoxacarb acts both by contact and by ingestion. Appel (2003) reported that indoxacarb gel baits (0.25%) were relatively nonrepellent (≈ 30%) and had a positive maximum performance index value (≈ 100) in Ebeling choice box experiments. However, a pyrethroid-resistant strain of German cockroach was found to be significantly resistant to indoxacarb gel baits (Appel, 2003). The 0.25% indoxacarb bait and a 0.25% abamectin bait (with the same matrix) were equally toxic, but indoxacarb performed faster in Ebeling choice box experiments and performed better in reducing visual counts of German cockroaches in an infested kitchen.

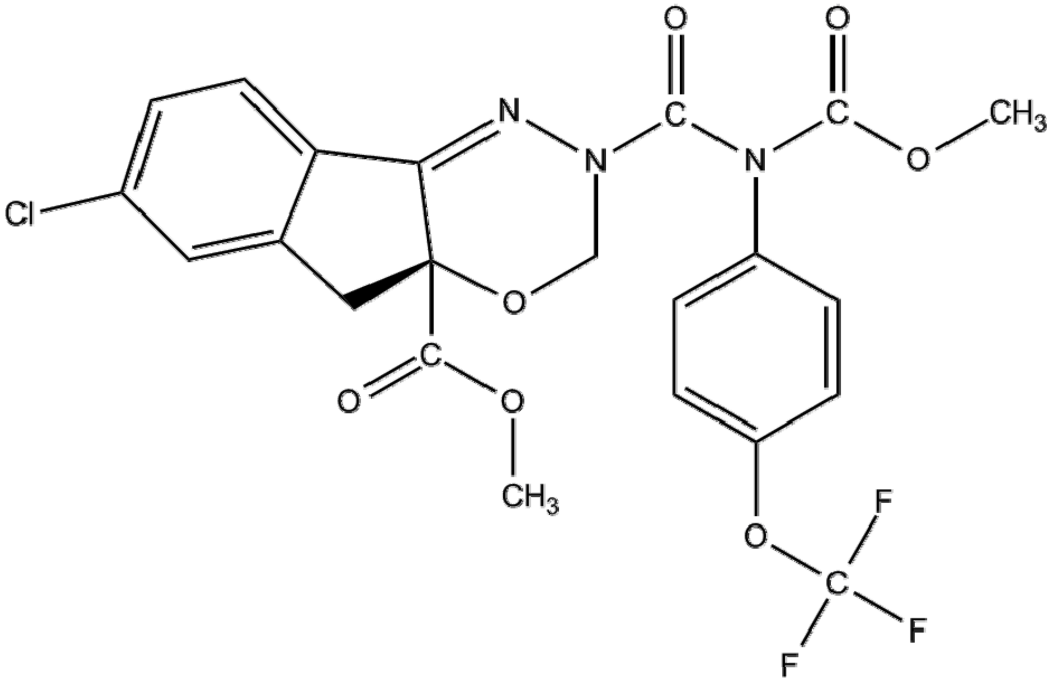

Figure 2.5: Chemical structure of indoxacarb