BIOLOGICAL FITNESS, RESISTANCE CHARACTERIZATION, RESISTANCE RISK ASSESSMENT AND EVALUATION OF SELECTED BAITS ON FIPRONIL- AND INDOXACARB BAIT-SELECTED STRAINS OF THE GERMAN COCKROACH, *Blattella germanica* (LINNAEUS) (DICTYOPTERA: BLATTELLIDAE)

by

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TABLE OF CONTENTS

PAGE

Acknowledgement ii

Table of Contents iv

List of Tables x

List of Figures xii

List of Plates xiv

Abstrak xv

Abstract xvii

CHAPTER ONE – GENERAL INTRODUCTION 1

CHAPTER TWO – LITERATURE REVIEW

2.1 Cockroach (General) 4

2.2 Biology of the German Cockroach 6

2.3 Medical and Economic Importance of Cockroaches 9

2.4 Conventional Control Methods 11

2.5 Insecticide Resistance 13

2.6 Insecticide Resistance in German Cockroach 15

- 2.6.1 History 15
- 2.6.2 Cross-resistance 28

2.7 Resistance Mechanisms 29

- 2.7.1 Reduced Cuticular Penetration 30
- 2.7.2 Metabolic resistance 31
  - 2.7.2.1 Monooxygenase 32

2.7.2.2 Esterase 34

2.7.2.3 Glutathione S-Transferase 36

2.7.3 Target-site Insensitivity 37

2.8 Development of Insecticide Resistance 39

2.8.1 Resistance Risk Assessment 41

2.9 Alternative Control Strategy – Bait Formulation 44

CHAPTER THREE – COMPARISON OF BIOLOGICAL FITNESS BETWEEN SUSCEPTIBLE AND INSECTICIDE-RESISTANT GERMAN COCKROACH

3.1 INTRODUCTION 47

3.2 MATERIALS AND METHODS 49

3.2.1 Cockroach Strains 49

3.2.2 Nymphal Development 49

3.2.3 Fecundity and Longevity 51

3.2.4 Ootheca Measurement 52

3.2.5 Population Growth Parameters 52

3.2.6 Data Analysis 52

3.3 RESULTS 53

3.3.1 Nymphal Development 53

3.3.2 Preoviposition Periods 57

3.3.3 Incubation Periods 57

3.3.4 Fecundity 61

3.3.5 Nymphal Survivorship 63

3.3.6 Ootheca Measurement 63

3.3.7 Adult Sex Ratio 63

3.3.8 Adult Longevity 66

3.3.9 Population Growth Parameters 66

3.4 DISCUSSION 69

CHAPTER FOUR – INDOXACARB RESISTANCE IN GERMAN COCKROACH: DETECTION OF CROSS-RESISTANCE AND DEVELOPMENT

4.1 INTRODUCTION 72

4.2 MATERIALS AND METHODS 74

4.2.1 Cockroach Strains 74

4.2.2 Chemicals 75

4.2.3 Topical Bioassay 75

4.2.4 Bait Assay 76

4.2.5 Bait Selection 76

4.2.6 Synergism and Biochemical Assay 77

4.2.7 Data Analysis 79

4.3 RESULTS 80

4.3.1 Baseline Susceptibility 80

4.3.2 Bait Evaluation 84

4.3.3 Correlations of LD_{50} and RR_{50} Values 84

4.3.4 Bait Selection 84

4.3.5 Synergism Study 87

4.3.6 Biochemical Assay 91

4.4 DISCUSSION 91

CHAPTER FIVE – FIPRONIL RESISTANCE IN GERMAN COCKROACH: DETECTION OF MECHANISM AND DEVELOPMENT

5.1 INTRODUCTION 98

5.2 MATERIALS AND METHODS 100

- 5.2.1 Cockroach Strains 100
- 5.2.2 Insecticides and Synergists 100
- 5.2.3 Topical Assay 101
- 5.2.4 Bait Evaluation 102
- 5.2.5 Bait Selection 102
- 5.2.6 Biochemical Assay 103
- 5.2.7 Detection of *Rdl* Mutation 106
- 5.2.8 Statistical Analysis 108

5.3 RESULTS 109

- 5.3.1 Fipronil and Dieldrin Susceptibility 109
- 5.3.2 Fipronil Synergism 109
- 5.3.3 Bait Evaluation 109
- 5.3.4 Bait Selection 114
- 5.3.5 Relationship between Fipronil and Dieldrin Susceptibility 114
- 5.3.6 Biochemical Assay 120
- 5.3.7 Detection of *Rdl* Mutation 120

5.4 DISCUSSION 123

CHAPTER SIX – RESISTANCE RISK ASSESSMENT OF GERMAN COCKROACH TO NOVEL INSECTICIDES FIPRONIL AND INDOXACARB

6.1 INTRODUCTION 130

6.2 MATERIALS AND METHODS 132

- 6.2.1 Cockroach Strains 132
- 6.2.2 Chemicals 133
- 6.2.3 Selection for Resistance 133
- 6.2.4 Topical Assay 134
- 6.2.5 Data Analysis 134
- 6.2.6 Estimation of Realized Heritability 135
- 6.2.7 Projected Rates of Resistance Development 136

6.3 RESULTS 136

6.4 DISCUSSION 143

CHAPTER SEVEN – EVALUATION OF SEVERAL BAIT FORMULATIONS EFFICACY AGAINST LABORATORY-SELECTED STRAINS OF GERMAN COCKROACH UNDER LABORATORY CONDITION

7.1 INTRODUCTION 147

7.2 MATERIALS AND METHODS 149

- 7.2.1 Cockroach strains 149
- 7.2.2 Insecticides 149
- 7.2.3 Topical Assay 150

7.2.4 Bait Evaluation 150

7.2.5 Statistical Analysis 151

7.3 RESULTS 152

7.3.1 Topical Assay 152

7.3.2 Bait Evaluation 152

7.4 DISCUSSION 155

SUMMARY AND CONCLUSIONS 161

REFERENCES 167

VITA 210

LIST OF TABLES

		PAGE
Table 2.1	Selected insecticide resistance studies in the German cockroach from 1953-2013.	16
Table 3.1	Insecticide resistance profiles of all strains of the German cockroach used in this study.	50
Table 3.2	Nymphal development of all strains of the German cockroach.	54
Table 3.3	Mean preoviposition, incubation period and number of nymphs produced per oothecae for the first and subsequent oothecae in all strains of the German cockroach.	58
Table 3.4	Total number of nymphs produced per female and nymphal survivorship (%) for all strains of the German cockroach.	64
Table 3.5	Ootheca measurements for all strains of the German cockroach.	65
Table 3.6	Mean longevity of adult males and females for all strains of the German cockroach.	67
Table 3.7	Population growth parameters for all strains of the German cockroach.	68
Table 4.1	Toxicity of eight insecticides against all strains of the German cockroach at 48 hours post-treatment.	81
Table 4.2	Evaluation of effectiveness of Advion® (Indoxacarb 0.6%) cockroach gel bait evaluation against all strains of the German cockroach.	85
Table 4.3	Pairwise correlations between LD_{50} and RR_{50} values of the insecticides tested on all strains of the German cockroach.	86
Table 4.4	Toxicity of several insecticides towards EHI susceptible and three indoxacarb-selected strains of the German cockroach.	88
Table 4.5	Synergism effect of PBO, DEF and both on the toxicity of deltamethrin on EHI susceptible and F_3 generations of three bait-selected strains.	90

Table 4.6 Biochemical assays on the EHI susceptible and three indoxacarb-selected (Parental and F_3 generation) strains of the German cockroach. 92

Table 5.1 Toxicity of fipronil and dieldrin against six strains of the German cockroach at 48 h posttreatment. 110

Table 5.2 Synergism of fipronil + PBO and/or DEF against six strains and three selected populations of the German cockroach. 111

Table 5.3 Evaluation of effectiveness of Goliath® (fipronil 0.05%) cockroach gel bait against six strains of the German cockroach. 113

Table 5.4 Toxicity of dieldrin and fipronil against three fipronil-selected strains and the EHI susceptible strain of the German cockroaches. 115

Table 5.5 Evaluation of effectiveness of Goliath® (fipronil 0.05%) cockroach gel bait against three selected cockroach strains for every generation. 117

Table 5.6 Biochemical assays against the EHI susceptible and three fipronil-selected (F_3 generation) strains of the German cockroach. 121

Table 5.7 Distribution of *Rdl* genotypes in the EHI susceptible and three fipronil-selected (parental and F5 generation) strains of the German cockroach. 122

Table 6.1 Estimation of the response to selection (*R*) and selection differential (*S*) of fipronil- and indoxacarb-selected population of the German cockroach. 140

Table 7.1 Toxicity of seven insecticides against two insecticide-selected strains and the EHI susceptible strain of the German cockroach. 153

Table 7.2 Evaluation of the effectiveness of seven cockroach gel bait formulations against two insecticide-selected strains and the EHI susceptible strain of the German cockroach. 154

LIST OF FIGURES

		PAGE
Figure 3.1	Cumulative duration of the first five instar stages for all strains of the German cockroach.	56
Figure 4.1	LT_{50} of all generations of three indoxacarb-selected cockroach strains through bait assays from parental to F_5 generation.	89
Figure 5.1	Direct sequencing chromatograph of three genotypes of cockroach individuals. The 302 mutation site is boxed. Homozygous susceptible; Ala302/Ala302, heterozygous; Ala302/Ser302 and homozygous resistant; Ser302/Ser302.	107
Figure 5.2	Resistance ratio at LT_{50} of several generations of three fipronil-selected cockroach strains determined by bait assays from the parental to the F_5 generation.	118
Figure 5.3	Linear relationship between LD_{50} of dieldrin and LD_{50} of fipronil in field-collected strains of German cockroach.	119
Figure 6.1	Development of fipronil toxicity in fipronil-selected *B. germanica* from parental to F7 generations. (Results for parental to F5 generations was collected from Chapter five). The error bars represent the 95% fiducial limit of the observed LD_{50}.	137
Figure 6.2	Development of indoxacarb toxicity in indoxacarb-selected *B. germanica* from parental to F7 generations. (Results for parental to F5 generations was collected from Chapter four). The error bars represent the 95% fiducial limit of the observed LD_{50}.	138
Figure 6.3	Effect of three different realized heritability [(a) h^2 = 0.600, (b) h^2 = 0.360, and (c) h^2 = 0.336] on the number of generations required for a 10-fold increase in LD_{50} of fipronil at three different slopes and different selection mortality (i).	141
Figure 6.4	Effect of three different realized heritability [(a) h^2 = 0.475, (b) h^2 = 0.376, and (c) h^2 = 0.197] on the number of generations required for a 10-fold increase in LD_{50} of indoxacarb at three different slopes and different selection mortality (i).	142

Figure 7.1 Cumulative mortality (%) of all bait formulations up to 2 weeks post treatment of two selected and EHI susceptible strains of the German cockroach. 156

LIST OF PLATES

PAGE

Plate 2.1 Adult male of the German cockroach, *Blattella germanica* (L.) 8

KETEGAPAN BIOLOGI, PENCIRIAN KERINTANGAN, PENILAIAN RISIKO KERINTANGAN DAN PENGUJIAN UMPAN TERPILIH PADA STRAIN LIPAS JERMAN, *Blattella germanica* (LINNAEUS) (DICTYOPTERA: BLATTELLIDAE) YANG DIPILIH OLEH UMPAN FIPRONIL DAN INDOXACARB

ABSTRAK

Kajian ini berfokus pada kerintangan insektisid pada lipas Jerman.Beberapa aspek yang telah disiasat termasuk ketegapan biologi, ketoksikan insektisid, potensi kerintangan silang, peningkatan kerintangan dan penilaian risiko, mekanisme kerintangan yang terlibat serta ujian keberkesanan umpan.

Ketegapan biologi yang terpilih telah dibandingkan antara lipas Jerman yang rintang insektisid dan yang rentan insektisid. Kebanyakan strains rintang menunjukkan tiada perbezaan yang signifikan dalam tempoh perkembangan nimfa, tempoh praoviposisi, tempoh pengeraman, penghasilan nimfa dan ooteka, ukuran ooteka, ketahanan hidup nimfa dan tempoh hayat berbanding dengan strain rentan. Keputusan ini menunjukkan bahawa allele kerintangan adalah tidak memudaratkan dalam aspek ketegapan.

Sepuluh insektisid dari kelas yang berbeza digunakan dalam bioassay topikal untuk menentukan tahap kerintangan insektisid. Semua strain lapangan lipas Jerman menunjukkan kerintangan yang rendah atau tiada kerintangan terhadap acetamiprid (0.7–1.9x), imidacloprid (1.6–2.5x), chlorantraniliprole (2.3–4.0x), bendiocarb (2.1–2.7x) dan fipronil (1.6–2.8x), tahap kerintangan yang sederhana terhadap indoxacarb (2.5–9.9x) dan chlorpyrifos (2.6–8.7x), tahap kerintangan yang tinggi terhadap DDT (>2.6x) dan deltamethrin (5.8–55.6x). Korelasi positif yang signifikan telah dikesan antara ketoksikan dieldrin dengan fipronil, mencadangkan bahawa kerintangan silang antara dua insektisid ini. Strain terpilih fipronil didapati berkembang kerintangan kepada fipronil dan dieldrin selepas pemilihan lima generasi, manakala strain terpilih indoxacarb dikesan berkembang kerintangan terhadap indoxacarb sahaja. Keputusan ini menunjukkan bahawa proses pemilihan telah didapati telah dialih kepada mekanisme kerintangan itu yang indoxacarb spesifik. Kedua-dua kerintangan insektisid telah dibuktikan bebas daripada laluan metabolik melalui kajian sinergisme dan biokimia. Kerintangan fipronil dalam strain lipas kami disahkan disebabkan oleh mutasi A302S *Rdl* pada reseptor GABA.

Tiga strain lipas digunakan untuk menilai risiko kerintangan terhadap dua insektisid, fipronil dan indoxacarb. Pewarisan yang sebenar (h^2) terhadap kerintangan fipronil dalam strain lipas kami berjulat dari 0.336–0.600, manakala kerintangan indoxacarb h^2 berjulat dari 0.197–0.475. Kami meramalkan bahawa 3–21 dan 2–17 generasi adalah diperlukan untuk berkembang kepada 10 kali ganda kerintangan terhadap fipronil dan indoxacarb masing-masingnya, berdasarkan kepada semua kombinasi yangberkemungkinan antara anggaran cerun dan h^2 di bawah tekanan pemilihan 50–90% mortaliti.

Berdasarkan asei topikal, strain lipas terpilih fipronil mempamerkan kerintangan yang tinggi dan sangat tinggi terhadap fipronil (51.7x), indoxacarb (170.4x) dan dieldrin (3257.1x), manakala strain terpilih indoxacarb hanya menunjukkan kerintangan yang tinggi terhadap indoxacarb (387.3x). Secara umumnya, kedua-dua strain terpilih kekal rentan terhadap semua formulasi umpan. Walau bagaimanapun, kami memerhatikan tahap peningkatan kerintangan silang yang rendah terhadap insektisid lain, mengesyorkan bahawa kedua-dua populasi rintang berkemungkinan kerintangan terhadap formulasi umpan pada masa depan.

BIOLOGICAL FITNESS, RESISTANCE CHARACTERIZATION, RESISTANCE RISK ASSESSMENT AND EVALUATION OF SELECTED BAITS ON FIPRONIL- AND INDOXACARB BAIT-SELECTED STRAINS OF THE GERMAN COCKROACH, *Blattella germanica* (LINNAEUS) (DICTYOPTERA: BLATTELLIDAE)

ABSTRACT

This study focuses on insecticide resistance in the German cockroach. Several aspects were investigated, including biological fitness, insecticide toxicity, cross-resistance potential, resistance development and risk assessment, resistance mechanisms involved as well as bait performance evaluation.

Selected biological fitness were compared between insecticide-resistant and insecticide-susceptible German cockroaches. Most resistant strains showed no significant difference in nymphal development period, preoviposition period, incubation period, nymphal and oothecal production, ootheca measurements, nymphal survivorship, and adult longevity compared to those of the susceptible strain. These results indicate that the resistant allele is not deleterious in aspect of fitness.

Ten insecticides from different classes were used in topical bioassay to determine insecticide resistance level. All field-collected strains of the German cockroach showed low or no resistance towards acetamiprid (0.7–1.9x), imidacloprid (1.6–2.5x), chlorantraniliprole (2.3–4.0x), bendiocarb (2.1–2.7x) and fipronil (1.6–2.8x), moderate levels of resistance to indoxacarb (2.5–9.9x) and chlorpyrifos (2.6–8.7x), high levels of resistance to DDT (>2.6x) and deltamethrin (5.8–55.6x). Significant positive correlation was detected between toxicity of fipronil and dieldrin,

suggesting that cross-resistance between these two insecticides. Fipronil-selected strains were found to develop resistance to fipronil and dieldrin after five generations of selection, whereas indoxacarb-selected strains were detected to increase resistance to indoxacarb only. This result shows that selection process appeared to have shifted the resistance mechanism to one that is indoxacarb specific. Both insecticide resistances were proven to be independent from metabolic pathway through synergism and biochemical assays. Fipronil resistance in our cockroach strains was confirmed conferred by A302S *Rdl* mutation in GABA receptor.

Three cockroach strains were used to assess resistance risk to two insecticides, fipronil and indoxacarb. The realized heritability (h^2) of fipronil resistance in our cockroach strains ranged from 0.336–0.600, whereas h^2 of indoxacarb resistance ranged of 0.197–0.475. We predicted that 3–21 and 2–17 generations are required to develop 10-fold resistance to fipronil and indoxacarb, respectively, based on all possible combinations of these estimated slopes and h^2, under selection pressure of 50–90% mortality.

Based on topical assay, fipronil-selected cockroach strain exhibited high to very high resistance to fipronil (51.7x), indoxacarb (170.4x) and dieldrin (3257.1x) whereas indoxacarb-selected strain only showed high resistance to indoxacarb (387.3x). Generally, both selected strains remains susceptible to all bait formulations studied. However, we observed low level of cross-resistance to other insecticides, recommending that both resistant populations might potentially develop resistance to other bait formulations in future.

CHAPTER ONE

GENERAL INTRODUCTION

The German cockroach, *Blattella germanica* (L.), is one of the prominent pest insect in the urban environment. It has become a very successful insect pest in many parts of the world due to their rapid reproduction and high adaptability. In addition, world globalization has connected all countries together through a global transportation network and resulted in spreading the German cockroach throughout the world. The swift increase of cockroach populations in human environment has brought many serious economic and medical problems to the public, thereby giving a significant challenge to the field of entomology research and the pest management industry. German cockroach is recorded to transmit various pathogenic organisms, including bacteria, helminthes, protozoans and viruses (Brenner 1995, Lee 1997a, 2007, Lee and Ng 2009). Accidental ingestion or inhalation of cockroach allergen, found in cockroach dead body, fecal materials, saliva and chitin skin, may trigger allergy and asthma, especially among children (Helm et al. 1996, Yu and Huang 2000, Chapman and Pomes 2008). German cockroaches remain a domiciliary pest cockroach species in most of the countries whereas in South East Asian countries, such as Malaysia and Singapore, they are more predominant in hotel kitchens and food preparation outlets (Lee and Ng 2009).

Nowadays, chemical control remains a major method in German cockroach management, but the efficiency of this method has declined due to the development of resistance to various insecticides. Currently, German cockroach has been reported to be resistant or cross-resistant to almost all insecticide classes. This resistance issue is an important aspect to be observed and understood. Indeed, every resistance case is important in developing a better management programance and thus, improving human existence and the environment. Moreover, knowledge is always obtained from looking back and using previous experience to create an effective control strategy. Besides, cross-resistance is also another important issue to be discussed and investigated. It potentially limits the lifetime of a newly-introduced insecticide. By understanding the potential cross-resistance, mechanism and development of resistance, the efficiency of control method can be improved and the probability of control failure using new insecticides can also be minimized. The cross-resistance reports together with the survey of the resistance status of the populations are important final steps of the testing procedure for a newly-launched pest control material.

In order to achieve the aims that were previously mentioned, this study was carried out with several objectives:

1) To measure the life-history variables, including developmental period, fecundity as well as adult longevity of both sex, between field-collected and laboratory insecticide susceptible strains of *B. germanica*.
2) To inspect the insecticide resistance level of field-collected strains of *B. germanica* from Singapore through topical and bait assays, examine the resistance mechanism through synergism and biochemical studies after laboratory selection process.
3) To investigate the fipronil and dieldrin resistance in field-collected strains of *B. germanica*, determine potential cross-resistance between fipronil and dieldrin and elucidate the fipronil resistance mechanism through synergism, biochemical and molecular detection of target site mutation after selection process.

4) To assess the resistance risk in three strains of *B. germanica* to fipronil and indoxacarb based on laboratory bait selection.
5) To determine the susceptibility of several insecticides of fipronil- and indoxacarb-selected strains of *B. germanica* and evaluate the bait efficacy in controlling the two selected strains of *B. germanica* under laboratory condition.

CHAPTER TWO

LITERATURE REVIEW

2.1 Cockroach (General)

Cockroach is one of the most primitive insects that exist in this world since 350 millions year ago. The fact has been confirmed by the discovery of the oldest cockroach fossil from the Silurian sandstone (Wootton 1981).Its morphology nearly remains unchanged since the Carboniferious era until the present (Appel 1995). There is very limited difference between the discovered fossil and the present cockroaches based on the insect body plan. Cockroaches have a generalized internal and external anatomy pattern. The cockroaches are grouped under the order Blattodea and their characteristics are closely related to the order Mantodea (praying mantis), because they share some similar morphological and biological characteristics. Both of these insect orders are able to produce hard shell covered eggs, ootheca. In addition, there are some shared biological features between cockroaches (Blattodea) and termites (Isoptera) such as the presence of digesting flagellate protozoa in the gut found in several wood-feeding cockroach species (such as *Cryptocercus punctulatus*) and termites (Carpenter et al. 2009). The characteristic of oothecae production by the primitive termite *Mastotermes darwiniensis* (Frogg) provides further evidence for the close relationship between cockroaches and termites and it was believed that termites were actually evolved from a wood-feeding cockroach ancestor. In 2007, Inward et al. (2007) proposed that termites are actually social cockroaches through phylogenetic analysis and should be classified in the same order with cockroach (Blattodea).

Morphological, ecological and behavioral characteristics of cockroaches enable them to survive in varying habitats, from desserts, aquatic environments, todark caves. Cockroach diversity appears to be more concentrated in humid and warm tropical rainforest regions and less diverse in the temperate regions (Guthrie and Tindall 1968). There are several interesting and significant features in cockroach evolutionary trends. One of the characteristics in their biology is their reproduction patterns. Cockroaches may be oviparous (extrude their oothecae at the posterior of the abdomen and deposit them on a surface or carry them for the whole incubation period), ovoviviparous (extrude and rotate their oothecae, then retract into female's abdomen and life nymphs may emerge from the female) or viviparous (similar process with ovoviviparous, except nutrients and water are provided by the female during incubation period) (Roth 1970). Besides, very few cockroach species live completely solitary. In fact, most of the cockroaches show aggregation behavior during part of their life. Previous studies found that this aggregation behavior can shorten nymphal development period at least in the German (Izutsu et al. 1970) and American cockroaches (Wharton et al. 1967). This social interaction behavior potentially enable the transfer of protozoa from adult to immatures (Appel 1995), acceleration of female reproduction by stimulating juvenile hormone (Uzsak and Schal 2012), information transfer and collective decisions on shelter (Jeanson and Deneubourg 2007, Canonge et al. 2011) and feeding sites selection (Lihoreau and Rivault 2011) and kin recognition to avoid inbreeding (Lihoreau and Rivault 2010). Today, there are over 4500 species of roaches described, but only a limited number of species are associated with human environments and are classified as pests. Some of them are omnivores (cave cockroaches), scavengers, and also general feeders who feed on almost everything they encounter. One of the survival characteristic of pest cockroaches is they can eat almost everything in human habitations, including man-made materials such as plastic and rubber (Bell et al. 2007). Besides, their high adaptive ability has always brought problems to human living environments. The ease of accessing water in humid habitats and lesser fluctuations in temperature enable cockroach species to be widely distributed in the tropical and subtropical regions (Appel 1995).

In Singapore and Malaysia, there are eight common cockroach species, five large-size species and three small-size species, recorded by Yap et al. (1991), Lee et al. (1993), Lee and Lee (2000a) and Lee and Ng (2009). The large-size cockroach species are namely the American cockroach (*Periplaneta americana*) (Linnaeus 1758), Australian cockroach (*Periplaneta australasiae*) (Fabricius 1775), Brown cockroach (*Periplaneta brunnea*) (Burmeister 1838), Harlequin cockroach (*Neostylopyga rhombifolia*) (Stoll 1813) and Lobster cockroach (*Nauphoeta cinerea*) (Olivier 1789), whereas the small-size cockroach species are the Brown-banded cockroach (*Supella longipalpa*) (Fabricius 1798), German cockroach (*Blattella germanica*) (Linnaeus 1767) and Smooth cockroach (*Symploce pallens*) (Stephens 1835). In the South-east Asia regions, the American cockroach is the most common species found in residential areas especially in sewer properties, whereas German cockroach prefer to inhabit food preparation outlets such as kitchens, hawker stalls, restaurants, etc.

2.2 Biology of the German cockroach

Scientific Classification

Phylum: Arthropoda

Class: Insecta

Order: Blattodea

Family: Blattellidae

Binomial name: *Blattella germanica* (Linnaeus) 1767 (Plate 2.1)

The German cockroach, *Blattella germanica* (L.) is one of the most prominent household pests in the world. In Singapore and Malaysia, it is predominant in hotels and food preparation outlets and can be rarely found in residential premises. In contrast, in western countries such as the United States, it is a domiciliary pest cockroach species. The main reason is their preference to stay in warm and humid environment.

Basically, they are general feeders and able to feed on organic materials, but with fondness for starchy food. They undergo incomplete metamorphosis and have three life stages: egg, nymph and adult. The eggs are covered by a brown and purse-shaped capsule called, the egg case. The female will carry the egg case at the end of her abdomen until ready to hatch (Barson and Renn 1983). The ootheca is usually 7–9 mm in length, average 3mm in width and contains approximately 30–48 eggs. An adult female normally produces 4–8 oothecae during her lifetime. The egg stage takes about 3–4 weeks to hatch depending on the environmental conditions. The nymphs of German cockroach resemble the adult with undeveloped wings and reproductive organs. They are black in colour with a pale yellow to brown stripe in the middle of the dorsum. Nymphs undergo 5–7 molting processes in a period of 6–7 weeks in order to achieve maturity. Generally, female nymphs will take a longer time to reach adult stage than male nymphs. The adult body is about 10–15 mm in length, light brown in colour, and has two dark stripes separated by a pale band running down the pronotum. Both adult males and females are winged but they rarely fly and instead glide. On the average, adult cockroaches can live 4–6 months (Ross and Mullins 1995, Lee and Ng 2009).

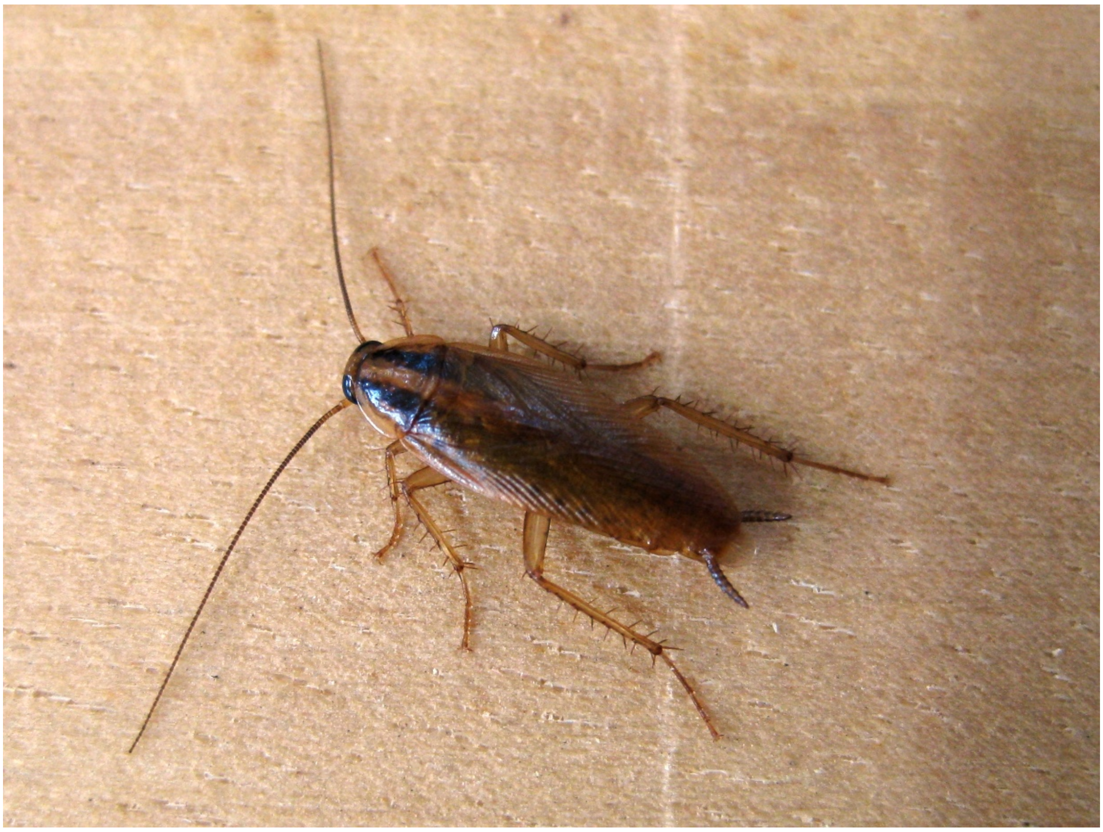

Plate 2.1 Adult male of the German cockroach, *Blattella germanica* (L.)

According to previous studies, differences regarding biological parameter exist between resistant and non-resistant individuals of cockroach because these resistant genes have a deleterious effect on the different aspects of biological fitness in resistant individuals. Several studies reported that the resistant phenotypes potentially reduced the biological fitness resulting in smaller ootheca, fewer nymphs produced (Grayson 1953, 1954), lower body weight, longer incubation period, preoviposition period and nymphal development period (Ross 1991, Lee et al. 1996a) and shorter longevity (Perkins and Grayson 1961).

2.3 Medical and Economic Importance of Cockroaches

The German cockroach has a high reproductive ability and they can rapidly colonize a newly infested environment. High infestation of cockroach will produce a significant unpleasant odor in the surrounding region. The excretion from cockroaches potentially contaminates food and kitchen implements especially in kitchen or food preparation areas. Food poisoning, dysentery and diarrhea are common diseases transferred through cockroach droppings. Their regurgitation and defaecation while feeding makesthe cockroach a potential mechanical vector of various pathogens causing health hazards in humans. Different species of bacteria, helminths, protozoans and virus that are pathogenic to humans in cockroach body are summarized by Brenner (1995), Lee (1997a, 2007) and Lee and Ng (2009). Besides, cockroachesare considered as important cause of asthma in many parts of the world, including Singapore (Eggleston and Arruda 2001). Accidental ingestion or inhalation of cockroach allergens may trigger allergy and asthma (Helm et al. 1996, Yu and Huang 2000, Chapman and Pomes 2008, Lee and Ng 2009). Their fecal materials, saliva, chitin skin and dead cockroach body contain allergen proteins which are known to stimulate allergic symptoms and increase the severity of asthma attacks, especially in children. A very high percentage of urban residents with asthma are sensitive to cockroach allergens. The appearance of total cockroach numbers in infested housing areas is positively correlated to the degree of cockroach sensitivity, suggesting that cockroach control can significantly reduce asthma simulation (National Research Council 2007).

There is limited or no detailed and published information about the accurate amount of money spent annually on German cockroach control. However, the economic losses caused by the German cockroach can be estimated through direct and indirect comparisons of total damage attributed to cockroaches. According to 1988 data (Douce and McPherson 1989), 40% (US49.66 million) of household and structural damages was accounted by cockroaches. Besides, the pesticide use survey report from the Environmental Protection Agency (EPA) showed that at least US 20.7 million was used to treat cockroachess in the USA in 1990 although cockroaches were not considered to be a major problem (Whitmore et al. 1992). In a separate survey conducted by professional pest control companies, the National Pest Control Association (NPCA) found that cockroaches were the most important household pest in the USA and that German cockroachesare the predominant species. Estimates showed that 14,250 professional pest control industries have hired 66,600 workers in servicing 12 millions dwellings, which covered most of the 288,000 food outlets, 480,000 restaurants and commercial kitchens, and 66,000 hotels as well as motels (Brenner 1995).

German cockroaches affect our economics not only in terms of money spent for controlling, but also in other less obvious ways. Due to their general feeding behaviour (omnivorous), most of our food is vulnerable at every stage of production, including during transition and storage. The food can be easily infested by the cockroaches prior to consumption. German cockroaches are also widespread in the food preparation industries and there must be some amount of federal tax revenues accounted to protect the food supply. In addition, German cockroach has a high reproductive ability and they can easily spread and expand their distribution among the building structures, non-food available areas. However, no published data is available to estimate the physical damage caused by cockroaches to electronic equipment or kitchen appliances. Obviously, there is a significant cost in repairing damage attributed by this insect accounted by the homeowner when this insect dominantly infested the house (Brenner 1995).

2.4 Conventional Control Methods

Chemical control is the major method in German cockroach management nowadays. Many conventional insecticides, targeting the insect nervous system after entering the body, were used in the control. The chemicals normally enter the insect's body through oral ingestion or penetrate through cuticular absorption by direct contact or vapor exposure and subsequently affecting the nervous system as well as physiological metabolisms. Since the early of 1950s when organochlorine insecticides were first introduced, chemical insecticides have become an important aspect in pest management (Dent 2000). Among the organochlorine compounds, lindane, DDT, dieldrin and chlordane are considered most suitable for German cockroach management. They were slow-acting but long-lasting when applied as residual. From mid 1950 to 1970, insecticides classes targeted on blocking action of acetylcholinesterase, such as carbamates and organophosphates, were mainly used for pest management. Carbaryl, propoxur and bendiocarb were cabamates formulated for the control of German cockroaches. There were several compounds in the organophosphorous group of major significance in German cockroach control, such as acephate, chlorpyrifos, diazinon, dichlorvos, fenitrothion, iodofenphos, malathion, pirimiphos-methyl, propetmphos and trichlorphon (Wickham 1996). Pyrethroid is actively being used in controlling cockroach after the mid 1960 due to its rapid action (knockdown and flushing effects) and low toxicity against mammals (Wickham 1996, Lee and Ng 2009). Pyrethroid compounds are group of synthetic insecticides that been derived from natural pyrethrins which can be obtained through the extraction of the dried flower heads of the plant *Chrysanthemum cinerariaefolium*. Pyrethroids are generally esters, formed from acid and alcohol components, and have greater stability in light than natural pyrethrins. Pyrethroids can be divided into two groups, type 1 and type 2 (Gammon et al. 1981, Yu 2008), based on their effects on sensory neurons in American cockroaches. A lot of commercial pyrethroid-based products are available in the market, such as Baygon, Raid, etc. Pyrethroids have often been used in residual formulations (spray or dust). Spraying and dusting methods fully take advantages of cockroach crawling behavior and also their preference to be “touched” on the ventral side of the body (Berthold and Wilson 1967). Cockroaches are killed by absorbing the toxin from the residual deposit along the treated area. This application must be repeated with different doses at suitable intervals in order to achieve good and effective control. It was recommended that treatment should be initiated with higher level of insecticide dosage to “wipe out” an infestation and followed by a maintenance phase with lower dosage at selected intervals.

2.5 Insecticide Resistance

Insecticide resistance has become a major threat in pest management industry, whether in agricultural or household insects. The Insecticide Resistance Action Committee (IRAC) defines resistance as the “heritable change in susceptibility of a pest population that is exhibited in the repeated failure of a compound to obtain the expected level of field control”. Insecticide resistance is different from insecticide tolerance. Tolerance is a natural ability of an insect population to withstand certain level of toxic effect and it can be developed in one generation as a result of physiological changes. The ability will disappear once the selection pressure has been removed (Yu 2008). Insect always develop resistance approximately a decade post-introduction of a new insecticide (Jorgen 2004). The invention of a new insecticide is not an easy and fast process and most of the chemicals that were commonly used shared some similarity in target sites (nervous system) (Emden and Service 2004). Indeed, resistance problem is a significant challenge facing agricultural production, health protection and the industrial pest management.

During the early 1950s, resistance case was very rare and most of the wild insect populations were fully susceptible to any kind of insecticide. But the situation changed after the first insecticide resistance problem was questioned by Melander (1914), who observed the high survival rate of the San Jose scale, *Quadraspidiotus perniciosus* (Comstock) after being treated with sulphur lime in Clarkston Valley of Washington, US. Published insecticide resistance cases increased dramatically after that and subsequently reaching a highest peak in the late 1970s and early 1980s (Whalon et al. 2008). Before 1989, various chemical selected-resistance cases have widely documented including modern synthetic organic chemicals (organochlorine, organophosphate, carbamate and pyrethroid) and also some inorganic chemicals such as sulphur and arsenicals (Onstad 2008). At present, more than 500 species of insects and mites show resistance toward about 410 types of various chemicals (Bellinger 1996, Whalon et al. 2008). An updated and more detailed arthropod resistance cases, systematized by species, geographical areas and resistant compounds, can be found in the Arthropod Pesticide Resistance Database (APRD) website (http://www.pesticideresistance.com). Among the resistance pests, some of them were reported to be multiple resistant towards a series of insecticide classes, which included the German cockroach *Blattella germanica* (Wen and Scott 1997, Wei et al. 2001, Kristensen et al. 2005), housefly *Musca domestica* (Linnaeus) (Wen and Scott 1999, Liu and Yue 2000, Kristensen et al. 2004), diamondback moth *Plutella xylostella* (Linnaeus) (Sayyed et al. 2005, Cao and Han 2006, Nehare et al. 2010, Pu et al. 2010), etc.

The intensity of pesticide use has repeatedly resulted in insecticide resistance and followed by control failures across most of the commonly use pesticides globally. In the early 1990s, Pimentel et al. (1991) and Pimentel et al. (1993) estimated the pesticide resistance impact on crop protection in the US as approximately 1.4–4 billion annually. Furthermore, mosquito resistance towards insecticides has also increased malaria cases in many developing countries and kills 3 million people annually (Whalon et al. 2008). Thus, the effect of pesticide resistance problem has very serious and important impact in human health protection and agricultural production.

There are several factors that contribute to the development of pesticide resistance in insects and mites, which include host biological and ecological characteristics, frequency and intensity of pesticide exposure, existence of resistance allele in a pretreated population, cross- and multiple-resistance possibility, dose and toxicity relationship, etc (Whalon et al. 2008). Besides, the effectiveness of a pest management tactic may influence the possibility of the pest developing resistance towards that method (Onstad 2008). Recently, molecular genetic studies have revealed many detailed resistance mechanisms and unravelled certain novel insecticide mode of actions. This helps a lot in understanding the genetic and the metabolic of the resistance mechanism.

2.6 Insecticide Resistance in German cockroach

2.6.1 History

Regular insecticide selection pressures have also induced the development of insecticides resistance in German cockroach populations (Lee et al. 1996b, Chai and Lee 2010). The first insecticide resistance case in German cockroach was reported by Heal et al. (1953) in Corpus Christi, Texas, U.S. The author found difficulty in controlling a field German cockroach using chlordane and revealed that the cockroach population possessed an extreme resistance degree towards chlordane (>100x). In the 1950s and 1960s, resistance cases towards DDT, chlordane and lindane were widely documented (Cochran 1995). After the loss of organochlorine insecticides, the organophosphate insecticides became dominant in cockroach management. However, in the mid 1960s, several authors reported that some field cockroach populations started to exhibit resistance towards diazinon and malathion. Subsequently, resistance toward various insecticides such as carbamate and pyrethroid were slowly published in the 1970s and 1980s. At present, the German cockroach has developed resistance approximately up to 47 different chemicals. A selected insecticide resistance study is summarized in Table 2.1.

Table 2.1 Selected insecticide resistance studies in German cockroach from 1953-2013.

Insecticide	Method[a]	RR[b]	Mechanism[c]	Location	Reference
Organochlorine					
DDT	T(SC)	5–6	–	Texas, U.S.	(Heal et al. 1953)
	D	1.4–1.9	–	U.S.	(Fish and Isert 1953)
	T(SC)	4–12	–	Germany & France	(Webb 1961)
	D	4–7	–	Hawaii, U.S.	(Ishii and Sherman 1965)
	D	10	–	Australia	(Hooper 1969)
	D	>40	(Reduced penetration)	Virginia, U.S.	(Collins 1973)
	T(GS)	3.8	–	Bulgaria	(Gecheva 1991)
	D	>6.1	(*kdr*)	Malaysia	(Lee et al. 1996b)
	T (GJ)	(7%)	(*kdr*)	Malaysia	(Lee and Lee 1998)
	T (GJ)	1.3–40.7	(*kdr*)	Malaysia	(Lee et al. 1999)
	D	>100	–	Florida, U.S.	(Gondhalekar et al. 2011)
Endosulfan	T(GJ)	1.1–2.5	–	Malaysia	(Lee et al. 1999)
Lindane	T(SC)	10–12	–	Texas, U.S.	(Heal et al. 1953)
	D(LC)	3.8–5.7	–	Texas, U.S.	(Grayson 1954)
	D	28–39	–	Hawaii, U.S.	(Ishii and Sherman 1965)
Chlordane	T(SC)	>100	–	Texas, U.S.	(Heal et al. 1953)
	D	1.8–108.6	–	U.S.	(Fish and Isert 1953)
	D(LC)	111.7–275.7	–	Texas, U.S.	(Grayson 1954)
	T(SC)	>25	–	California, U.S.	(Micks 1960)
	T(SC)	1.2–14.4	–	Germany & France	(Webb 1961)
	D	452	–	Louisiana, U.S.	(Bennett and Spink 1968)
	T(GJ)	8.2	–	Maryland, U.S.	(Nelson and Wood 1982)

Dieldrin	D	1.2–68	–	U.S.	(Fish and Isert 1953)
	T (GJ)	1.2–4.4	–	Malaysia	(Lee et al. 1999)
	D	13–2030/ 15–1270	*Rdl*	Denmark	(Hansen et al. 2005, Kristensen et al. 2005)
	D	>100	–	Florida, U.S.	(Gondhalekar et al. 2011)
Organophosphate					
Chlorpyrifos	T(SC)	1.3	–	New Jersey, U.S.	(Schal 1988)
	T (GJ)	~1–10	–	U.S.	(Cochran 1989)
	D	~20	Monooxygenase, Hydrolase	U.S.	(Siegfried et al. 1990)
	D	~3–10	Monooxygenase	U.S.	(Scott et al. 1990)
	D	1.4–29.7	–	U.S.	(Rust and Reierson 1991)
	D(GT)	7.1	–	Florida, U.S.	(Moss et al. 1992)
	D	5.4	–	Florida, U.S.	(Moss et al. 1992)
	D	~6–9	Esterase	U.S.	(Prabhakaran and Kamble 1993)
	D	3.2–17.3	–	U.S.	(Rust et al. 1993)
	T(GJ)	1.2–2.2	–	U.S.	(Rust et al. 1993)
	D(LC)	8–462	Monooxygenase (6 of 14strains), altered acetylcholinesterase (1 of 14strains)	U.S.	(Hemingway et al. 1993a)
	D(LC)	6–9	–	U.S.	(Hostetler and Brenner 1994)
	D (thoracic)	5–56.3	–	U.S.	(Scharf et al. 1995)
	T(GJ)	1.3–5.9	–	U.S.	(Scharf et al. 1995)
	D(tarsal)	7.6–37.5	–	U.S.	(Scharf et al. 1995)
	D	2.4–7.6	–	Malaysia	(Lee et al. 1996b)
	D	7	–	Georgia, U.S.	(Valles and Yu 1996)
	T(GJ)	1.4–>50	–	U.S.	(Scott and Wen 1997)

	T(GJ)	1.1–4.3	Monooxygenase, Esterase	Malaysia	(Lee 1998)
	D	5.6	(Esterase)	U.S.	(Park and Kamble 1998)
	T(GJ)	1.1–4.3	Esterase	Malaysia	(Lee et al. 1999)
	D(LC)	5.8–11.8	–	Cuba	(Diaz Pantoja et al. 2000)
	T(GJ)	1.2–7.5	Monooxygenase, Esterase	Peninsular Malaysia	(Lee and Lee 2004)
	D	1.9–28.8	–	Taiwan	(Pai et al. 2005)
	D	12.6	–	Korea	(Chang et al. 2009)
	D	2–13	–	Korea	(Chang et al. 2010)
	D	1.5–22.8	Monooxygenase, Esterase	Singapore	(Chai and Lee 2010)
	D	25.6	(Metabolic)	Florida, U.S.	(Gondhalekar et al. 2011)
Chlorpyrifos-methyl	T(GJ)	1–2.9	–	Malaysia	(Lee et al. 1999)
	D	2–8	–	Korea	(Chang et al. 2010)
Diazinon	D	1.2–2.4	–	U.S.	(Fish and Isert 1953)
	D(SC)	2.5–6.3	–	Texas, U.S.	(Grayson 1965)
	D	13	–	Louisiana, U.S.	(Bennett and Spink 1968)
	D	26	(Reduced penetration)	Virginia, U.S.	(Collins 1973)
	T(GJ)	3.7	–	Maryland, U.S.	(Nelson and Wood 1982)
	T(SC)	1.8	–	New Jersey, U.S.	(Schal 1988)
	T(GJ)	~1–10	–	U.S.	(Cochran 1989)
	T(GJ)	1.7–5.3	–	U.S.	(Rust et al. 1993)
	T(GJ)	1–3.7	–	Malaysia	(Lee et al. 1999)
Dichlorvos	T (GJ)	5.3-31.1	–	Bulgaria	(Gecheva and Ranchov 1994)
Fenitrothion	T(GJ)	1.1–4.1	Esterase	Malaysia	(Lee et al. 1999)
	D	17.7	–	Korea	(Chang et al. 2009)
Fenthion	D(SC)	2.7–5	–	Texas, U.S.	(Grayson 1965)
	D	11	–	Louisiana, U.S.	(Bennett and Spink 1968)
	D	8–17	–	Korea	(Chang et al. 2010)

Malathion	T(SC)	1.5–3	–	Germany & France	(Webb 1961)
	D(SC)	2.2–12.8	–	Texas, U.S.	(Grayson 1965)
	D	6.8–8.5	–	Hawaii, U.S.	(Ishii and Sherman 1965)
	D	110	–	Louisiana, U.S.	(Bennett and Spink 1968)
	D	27	(Reduced penetration)	Virginia, U.S.	(Collins 1973)
	T(GJ)	6.5	–	Maryland, U.S.	(Nelson and Wood 1982)
	D	~33	(Metabolic detoxification)	U.S.	(Bull et al. 1989)
	T(GS)	~1–>60	–	U.S.	(Cochran 1989)
	D/T	~3–10/ >60	Monooxygenase	U.S.	(Scott et al. 1990)
	T(GJ)	1.9–41.1	–	Malaysia	(Lee 1997b)
	T(GJ)	2–>275	Carboxylesterase (3 of 11 strains)	Malaysia	(Lee et al. 1999)
	D(LC)	5.5–>25	–	Cuba	(Diaz Pantoja et al. 2000)
Acephate	T(GS)	~1–2	–	U.S.	(Cochran 1989)
	T(GJ)	1.3	–	U.S.	(Rust et al. 1993)
Profenofos	D	4.1	–	Korea	(Chang et al. 2009)
Pyridafenthion	D	75.6	–	Korea	(Chang et al. 2009)
Pirimiphos-methyl	T(GJ)	1.3–7.1	Esterase	Malaysia	(Lee et al. 1999)
	D(LC)	3.4–24.8	–	Cuba	(Diaz Pantoja et al. 2000)
Propetamphos	T(GJ)	1.3	–	U.S.	(Rust et al. 1993)
Carbamate					
Carbaryl	D	~5	(Metabolic detoxification)	U.S.	(Bull et al. 1989)
	T(GJ)	2.5–9.8	–	Malaysia	(Lee et al. 1999)
Bendiocarb	D(LC)	5.6–6.2	–	England	(Barson and McCheyne 1978)
	T(GJ)	>80	Oxidase	U.S.	(Cochran 1987a)
	T(SC)	>100	–	New Jersey, U.S.	(Schal 1988)
	T(GC)	~1–>60	–	U.S.	(Cochran 1989)

	D/T	>10 (2 of 3 strains)/ >60	Monooxygenase, Hydrolase	U.S.	(Scott et al. 1990)
	D	6.7	–	Florida, U.S.	(Moss et al. 1992)
	D(LC)	6.8	–	Florida, U.S.	(Moss et al. 1992)
	T(GJ)	>21	–	U.S.	(Rust et al. 1993)
	D	46	Monooxygenase, Esterase	Georgia, U.S.	(Valles and Yu 1996)
	D	3.7–>62	–	Malaysia	(Lee et al. 1996b)
	T(GJ)	1.7–4.8	Acetylcholinesterase insensitivity (2 of 4 strains)	Malaysia	(Lee et al. 1997)
	T(GJ)	3–3.3	Monooxygenase, Esterase	Malaysia	(Lee and Lee 1998)
	T(GJ)	3.1–65.2	Monooxygenase, Esterase, Altered acetylcholinesterase (5 of 23 strains)	Malaysia	(Lee et al. 1999)
Propoxur	D	18	(Reduced penetration)	Virginia, U.S.	(Collins 1973)
	T(GJ)	13.3	–	Maryland, U.S.	(Nelson and Wood 1982)
	T(SC)	>100	–	New Jersey, U.S.	(Schal 1988)
	T(GS)	~1–>60	–	U.S.	(Cochran 1989)
	D	~3–10	–	U.S.	(Scott et al. 1990)
	D	~2–4	Esterase	U.S.	(Prabhakaran and Kamble 1993)
	T(GJ)	1.4–2.3	–	U.S.	(Rust et al. 1993)
	D(LC)	4–46	Monooxygenase (7 of 14 strains), Altered acetylcholinesterase (1 of 14 strains)	U.S.	(Hemingway et al. 1993a)
	D	2.8–91.6	Monooxygenase, Esterase, (*kdr*)	Malaysia	(Lee et al. 1996b)
	D	17	Monooxygenase	Georgia, U.S.	(Valles and Yu 1996)
	T(GJ)	1.7–9.8	Monooxygenase, Esterase	Malaysia	(Lee 1998)
	T(GJ)	1.2–1.4	(Esterase)	Malaysia	(Lee and Lee 1998)

	D	15.6	(Esterase)	U.S.	(Park and Kamble 1998)
	D	4–55	Esterase	U.S.	(Valles 1998)
	T(GJ)	1.3–11.5	Monooxygenase, Esterase, Altered acetylcholinesterase (5 of 23 strains)	Malaysia	(Lee et al. 1999)
	D(LC)	2.1–4	–	Cuba	(Diaz Pantoja et al. 2000)
	T(GJ)	1.5–>280	Monooxygenase, Esterase (a few strains), (Altered acetylcholinesterase)	Peninsular Malaysia	(Lee and Lee 2004)
	D	2.9–62.5	–	Taiwan	(Pai et al. 2005)
	D	3.9–21.5	Oxidase, Hydrolase, (Altered acetylcholinesterease)	Singapore	(Chai and Lee 2010)
	D	13.9	(Metabolic)	Florida, U.S.	(Gondhalekar et al. 2011)
	D	2.1–16.9	–	Indonesia	(Rahayu et al. 2012)
Dioxacarb	T(GJ)	1.5–25.4	–	Bulgaria	(Gecheva 1993)
Pyrethroid					
Bifenthrin	T(GJ)	1–2.2	–	Malaysia	(Lee et al. 1999)
	D	27.1	–	Korea	(Chang et al. 2009)
	D	46–159	–	Korea	(Chang et al. 2010)
Cyfluthrin	T(GS)	~1–6	–	U.S.	(Cochran 1989)
	D	87.5	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)
	-	>2	Monooxygenase, Esterase, GST, *kdr*	Three Continents	(Hemingway et al. 1993b)
	T(GJ)	>40	Metabolic	U.S.	(Cochran 1994d)
	T(GJ)	2.4–11.4	–	Iran	(Limoee et al. 2006)
β-cyfluthrin	D	3–468	Monooxygenase, Esterase, *kdr*	Singapore	(Chai and Lee 2010)
Cyhalothrin	D	40.6	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)

λ-cyhalothrin	-	>2	Monooxygenase, Esterase, GST, *kdr*	Three continents	(Hemingway et al. 1993b)
	D	2–88	Esterase	U.S.	(Valles 1998)
	D	21–67	–	U.S.	(Valles 1999)
	D(LC)	2.5–97	–	Cuba	(Diaz Pantoja et al. 2000)
	D	30.1	–	Korea	(Chang et al. 2009)
Cypermethrin	T(SC)	4.5	–	New Jersey, U.S.	(Schal 1988)
	D	4.8–19.4	*kdr*	U.S.	(Scott et al. 1990)
	D	103.6	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)
	D/ T	122.6/ 2.9	–	Virginia, U.S.	(Zhai and Robinson 1992)
	D/ (GT)	66.7/ 30.1	–	Florida, U.S.	(Moss et al. 1992)
	D	~2-5	Esterase	U.S.	(Prabhakaran and Kamble 1993)
	T(GJ)	4.3–20	–	U.S.	(Rust et al. 1993)
	-	>2	Monooxygenase, Esterase, GST, *kdr*	Three continents	(Hemingway et al. 1993b)
	D(LC)	23 (male) 21 (female)	–	U.S.	(Hostetler and Brenner 1994)
	T(GJ)	>50	Metabolic	U.S.	(Cochran 1994d)
	D (tarsal)	3.8–46.2	–	U.S.	(Scharf et al. 1995)
	D (thoracic)	3.4–7.8	–	U.S.	(Scharf et al. 1995)
	T(GJ)	1.2–5.5	–	U.S.	(Scharf et al. 1995)
	D	28	–	Georgia, U.S.	(Valles and Yu 1996)
	D	1.3–22.5	(*kdr*)	Malaysia	(Lee et al. 1996b)
	T(SC)	High/ moderate	–	Poland	Gliniewicz et al. 1996
	T(GJ)	1–>100	–	U.S.	(Cochran 1997)
	T(GJ)	1.2–1.7	–	Malaysia	(Lee 1998)

	D	17.3	(Esterase)	U.S.	(Park and Kamble 1998)
	D	3–159	Monooxygenase (5 of 12 strains), Esterase (10 of 12 strains)	U.S.	(Valles 1998)
	T(GJ)	1.2–3.5	–	Malaysia	(Lee et al. 1999)
	D(LC)	5.5–>360	–	Cuba	(Diaz Pantoja et al. 2000)
	D	93	Monooxygenase, Hydrolase	Florida, U.S.	(Valles et al. 2000)
	D	2.9	Microsomal esterase	U.S.	(Valles and Strong 2001)
	D	2–27.4	–	Taiwan	(Pai et al. 2005)
	T(GJ)	2.9–20.7	–	Iran	(Limoee et al. 2006)
	T(J)	2.2–2.3	Oxidase, Esterase	Iran	(Enayati and Haghi 2007)
	D	47.6	–	Korea	(Chang et al. 2009)
	T(GJ)	1.6–3.6	Monooxygenase	Indonesia	(Ahmad et al. 2009)
	D	16–29	–	Korea	(Chang et al. 2010)
	D	11.5–26.5	Monooxygenase	Kermanshah, Iran	(Limoee et al. 2011)
	D	86.5	–	Florida, U.S.	(Gondhalekar et al. 2011)
Deltamethrin	D	27.5 (1 of 3 strains)	–	U.S.	(Scott et al. 1990)
	D	6.4–23.6	(*kdr*)	Malaysia	(Lee et al. 1996b)
	T(GJ)	2–2.3	(*kdr*)	Malaysia	(Lee and Lee 1998)
	T(GJ)	1.1–2.9	(*kdr*)	Malaysia	(Lee et al. 1999)
	D(LC)	12–>250	–	Cuba	(Diaz Pantoja et al. 2000)
	D/ T	17.7–4235/ 2.2–22	–	Singapore	(Choo et al. 2000)
	D	480	Monooxygenase, Hydrolase	Alabama, U.S.	(Wei et al. 2001)
	D	47–480	*kdr* (1 of 4 strains)	Alabama, U.S.	(Pridgeon et al. 2002)
	T(GJ)/ D	1.2–35.7/ <20% (7 of 27 strains)	Monooxygenase, Esterase, (*kdr*)	Peninsular Malaysia	(Lee and Lee 2004)

	T(J)	2–2.2	Oxidase, Esterase	Iran	(Enayati and Haghi 2007)
	D	20.6	–	Korea	(Chang et al. 2009)
	D	61–160	–	Korea	(Chang et al. 2010)
	D	3–468	Monooxygenase, Esterase, *kdr*	Singapore	(Chai and Lee 2010)
Esfenvalerate	D	29.4	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)
	T(GJ)	>40	Metabolic	U.S.	(Cochran 1994d)
	D	20.7	–	Korea	(Chang et al. 2009)
	D	70–270	–	Korea	(Chang et al. 2010)
Fenvalerate	T(GJ)	~1–>60	–	U.S.	(Cochran 1989)
	D	97.7	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)
	-	>2	Monooxygenase, Esterase, GST, *kdr*	Three continents	(Hemingway et al. 1993b)
	T(GJ)	>40	Metabolic	U.S.	(Cochran 1994d)
	D	825	Monooxygenase, Esterase, GST, (*kdr*)	Indana, U.S.	(Wu et al. 1998)
Permethrin	T(GS)	~1–>100	–	U.S.	(Cochran 1989)
	D	45.1	Metabolic, (*kdr*)	Florida, U.S.	(Atkinson et al. 1991b)
	D	20	(Monooxygenase, Esterase, GST)	U.S.	(Anspaugh et al. 1994)
	T(GJ)	>90	Metabolic	U.S.	(Cochran 1994d)
	D	12	–	Georgia, U.S.	(Valles and Yu 1996)
	D	1.2–14.6	(*kdr*)	Malaysia	(Lee et al. 1996b)
	D	13.5	(Esterase)	U.S.	(Park and Kamble 1998)
	T(GJ)	1.3–17.6	(*kdr*), Monooxygenase (3 of 8 strains)	Malaysia	(Lee et al. 1999)
	T(SC) (KT)/ (M)/ D	17–27/ 4.2–6.5/ 4.1–4.7	Oxidase	Iran	(Ladonni 2000)
	D	97	Monooxygenase, Hydrolase	Alabama, U.S.	(Wei et al. 2001)