Insecticide Resistance Profiles and Synergism in Field Populations of the German Cockroach (Dictyoptera: Blattellidae) From Singapore

RU-YUAN CHAI AND CHOW-YANG LEE[1]

Urban Entomology Laboratory, Vector Control Research Unit, School of Biological Sciences, Universiti Sains Malaysia, 11800 Penang, Malaysia

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ABSTRACT The resistance profiles of 22 field-collected populations of the German cockroach, *Blattella germanica* (L.) (Dictyoptera: Blattellidae), from various localities in Singapore were determined by topical bioassay against novel and conventional insecticides from six classes: 1) pyrethroid (beta-cyfluthrin, deltamethrin), 2) carbamate (propoxur), 3) organophosphate (chlorpyrifos), 4) phenyl pyrazole (fipronil), 5) neonicotinoid (imidacloprid), and 6) oxadiazine (indoxacarb). Compared with a laboratory susceptible strain, resistance levels ranged from 3.0 to 468.0× for the pyrethroids, from 3.9 to 21.5× for the carbamate, from 1.5 to 22.8× for the organophosphate, from 1.0 to 10.0× for phenyl pyrazole, and were absent or low for the neonicotinoid (0.8–3.8×) and the oxadiazine (1.4–5.3×). One strain demonstrated broad-spectrum resistance to most of the insecticides. Synergism studies using piperonyl butoxide (PBO) and *S,S,S*-tributylphosphorotrithioate (DEF) in combination with a discriminating dose (LD_{99}) of selected insecticides were conducted to test for possible resistance mechanisms. Resistance to pyrethroid was reduced with PBO and DEF, suggesting the involvement of P450 monooxygenase and esterases in conferring resistance. Propoxur resistance also was suppressed with PBO and DEF, and coadministration of both synergists resulted in complete negation of the resistance, indicating the involvement of both P450 monooxygenase and esterase. In six *B. germanica* field strains evaluated, esterases were found to play a role in chlorpyrifos resistance, whereas the P450 monoxygenase involvement was registered in three strains. Additional resistance mechanisms such as *kdr*-type and *Rdl* mutation contributing toward pyrethroid and fipronil resistance, respectively, also may be involved in some strains in which the resistance levels were not affected by the synergists. We conclude that insecticide resistance is prevalent in field German cockroach populations in Singapore.

KEY WORDS *Blattella germanica*, insecticide resistance, synergism, resistance mechanism, Singapore

Heavy reliance on and high frequency of insecticide use have led to the development of resistance to insecticides. Insecticide resistance in the German cockroach, *Blattella germanica* (L.) (Dictyoptera: Blattellidae), is a challenging issue that has faced the pest management industry for many decades. This problem transcends geographical regions (Webb 1961, Bennett and Spink 1968, Horwood et al. 1991, Hemingway et al. 1993, Spencer et al. 1999, Ladonni 2001, Pai et al. 2005) and different classes of insecticides (Grayson 1965, Ishii and Sherman 1965, Ross and Bret 1986, Holbrook et al. 1999).

Enhanced metabolism is the major resistance mechanism in many strains of German cockroach (Siegfried and Scott 1992, Bull and Patterson 1993, Anspaugh et al. 1994, Valles 1998, Wu et al. 1998, Lee et al. 2000, Valles et al. 2000). Enzymes involved in the detoxification of insecticides are either present at a higher level or have enhanced activity in resistant strains of German cockroach compared with susceptible strains. Synergists such as piperonyl butoxide (PBO) and *S,S,S*-tributylphosphorotrithioate (DEF) can be used to provide indirect evidence about the possible metabolic mechanisms involved in resistance. PBO is an inhibitor of P450 monooxygenases, and DEF is a general inhibitor of esterases. By comparing the toxicity of an insecticide in the presence or absence of a synergist in a particular strain, one can deduce which metabolic system is responsible for conferring resistance to the insecticide and subsequently overcome it with an appropriate solution (Scott 1990).

Lee et al. (1996a), Lee and Lee (2002), and Ahmad et al. (2009) reported that insecticide resistance in the German cockroach is prevalent in Southeast Asia. A survey conducted by Choo et al. (2000) revealed high levels of deltamethrin resistance in populations of German cockroach in Singapore. Ten field-collected strains of the German cockroach that were trapped

[1] Corresponding author, e-mail: chowyang@usm.my.

Table 1. Information on field-collected German cockroach strains from Singapore used in this study

Strain	Premises	Mean wt of adult male ± SE (g)	Date of collection
EHI (susceptible)		0.0531 ± 0.0013	
Tampines Central	Shopping mall	0.0447 ± 0.0051	25 May 2005
Upper Thomson Road	Shopping mall	0.0491 ± 0.0051	25 May 2005
Joo Chiat Road	Pub	0.0447 ± 0.0016	8 June 2005
Biopolis Street	Food court	0.0489 ± 0.0016	8 June 2005
Tiong Bahru Road	Shopping mall	0.0474 ± 0.0036	8 June 2005
B1 Tampines Central	Restaurant	0.0495 ± 0.0013	8 June 2005
Bukit Timah Road	Food court	0.0489 ± 0.0013	10 June 2005
Bukit Merah Central	Coffee shop	0.0531 ± 0.0016	21 June 2005
Beach Road	Karaoke/Pub outlet	0.0454 ± 0.0017	30 June 2005
Boat Quay	Restaurant	0.0472 ± 0.0006	30 June 2005
Jalan Membina	Bakery	0.0485 ± 0.0012	8 July 2005
Victoria Street	Restaurant	0.0494 ± 0.0014	28 July 2005
Ang Mo Kio	Canteen	0.0538 ± 0.0023	28 July 2005
Jurong	Canteen	0.0449 ± 0.0012	1 Aug. 2005
Kallang Sector Road	Canteen	0.0502 ± 0.0017	2 Aug. 2005
Serangoon Central	Coffee shop	0.0524 ± 0.0013	17 Aug. 2005
Cavenagh Road	Food court	0.0509 ± 0.0016	19 Aug. 2005
Jelebu Road	Supermarket	0.0452 ± 0.0006	24 Nov. 2005
Bedok North	Supermarket	0.0510 ± 0.0013	28 Nov. 2005
Rivervale Crescent	Supermarket	0.0482 ± 0.0017	1 Dec. 2005
Geylang Road	Condominium bin chute	0.0472 ± 0.0012	12 Dec. 2005
Ghimmoh Road	Kitchen	0.0541 ± 0.0018	22 Dec. 2005

from various hotel kitchens demonstrated resistance to deltamethrin, with a resistance levels in one strain of >4,000-fold in comparison with a laboratory susceptible strain. However, no ensuing detailed report has been published regarding the insecticide resistance status in German cockroach populations from Singapore.

This study was conducted to determine the current status of insecticide resistance and to detect potential cross-resistance in field populations of German cockroaches from Singapore. In addition, possible resistance mechanisms in the resistant strains were investigated through synergism studies. A broad range of insecticides, including relatively newer compounds such as fipronil, imidacloprid, and indoxacarb, were used. Widening the scope of toxicity assays to include such new compounds is important because resistance and cross-resistance to these new compounds have been reported (Valles et al. 1997, Wen and Scott 1997).

Materials and Methods

Cockroach Strains. Twenty-two strains of German cockroach were collected from various localities (Table 1) in Singapore with the help of several pest control companies. An insecticide susceptible strain (EHI) was obtained from the Environmental Health Institute, National Environmental Agency, Singapore, and used as a standard for comparison.

The cockroaches were reared in plastic aquaria (38 by 22 by 27 cm) under laboratory conditions of 26 ± 2°C, 50 ± 10% RH, and a photoperiod of 12:12 (L:D) h, and food and water were provided ad libitum. Male cockroaches aged 1–3 wk old were segregated for study. Males were used because their weights are more uniform compared with those of females (Abd-Elghafar et al. 1990). The test insects were standardized for various biotic factors such as age, food, and time of testing to avoid possible variation in test results (El-Aziz et al. 1969, Lee et al. 1996b).

Insecticides. Technical grade deltamethrin (Bayer Environmental Science, Kuala Lumpur, Malaysia), propoxur (Bayer Environmental Science, Kuala Lumpur, Malaysia), chlorpyrifos (Dow AgroScience, Petaling Jaya, Malaysia), beta-cyfluthrin (Bayer Environmental Science, Kuala Lumpur, Malaysia), fipronil (PESTANAL, Sigma-Aldrich Laborchemikalien GmBh, Munich, Germany), imidacloprid (Bayer Australia Ltd., Sydney, Australia), and indoxacarb (DuPont Professional Products, Wilmington, DE) were used in this study. Stock solutions of these chemicals were prepared by dissolving the insecticides in analytical grade acetone (Sigma, St. Louis, MO).

Topical Bioassay. The cockroaches were subjected to topical assays to generate a LD_{50} value for each strain, as described by Lee et al. (1996a). Ten male cockroaches were anesthetized with a gentle dose of CO_2 (pressure, 20 kPa) for no >10 s. One microliter of a predetermined dose of insecticide was applied topically on the first abdominal sternite of individual cockroaches using a microapplicator (Burkard Scientific Ltd., Middlesex, United Kingdom) fitted with a size 27-gauge needle on a 1-ml hypodermic insulin glass syringe (Fortune WG Co., Munich, Germany). A series of four to six doses for each insecticide that resulted between >0 and <100% mortality was carried out and the experiment was replicated four times. Control cockroaches were treated with 1.0 μl of acetone. The mean weight of an adult male for each strain was determined by weighing five groups of 10 males, and data are shown in Table 1.

Treated cockroaches were maintained in clean polyethylene petri dishes containing a pellet of dog food and a moist cotton ball, with 10 cockroaches per container. Mortality was inspected at 48 h posttreatment. A cockroach was considered to be dead if it was unable to right itself to its normal posture within 2 min after being touched on the abdomen with a pair of forceps.

Data Analysis. All results were pooled and subjected to probit analysis using the POLO-PC (LeOra Software 1997) to estimate the LD_{50} and LD_{95} values. A nonoverlap of 95% fiducial limits was used to determine the significant differences between the values. All LD_{50} and LD_{95} values were expressed in micrograms per gram to avoid the possible effect of weight differences on insecticide susceptibility.

The resistance ratio at LD_{50} (RR_{50}) was calculated by dividing the LD_{50} values of the field strains with the corresponding lethal dose for the EHI susceptible strain. The resistance ratio was classified into the following five categories according to Lee and Lee (2004): ≤1, absence of resistance; >1 to ≤5, low resistance; >5 to ≤10, moderate resistance; >10 to ≤50, high resistance; and >50, very high resistance.

Table 2. Information on discriminating dose (LD_{99}) values obtained from the bioassay against the EHI susceptible strain

Insecticide	LD_{99} (μg/μl) (95% FL)	LD_{99} (μg/g) (95% FL)
Deltamethrin	0.046 (0.035–0.070)	0.866 (0.659–1.318)
β-Cyfluthrin	0.024 (0.017–0.055)	0.452 (0.320–1.036)
Propoxur	1.347 (0.948–2.387)	25.367 (17.853–44.953)
Chlorpyrifos	0.867 (0.506–6.542)	16.328 (9.529–123.202)

Synergism Studies. The insects were first topically treated with 1.0 μl of PBO (FMC Corporation, Middleport, NY) (100 μg per insect) or *S,S,S*-tributylphosphorotrithioate (DEF) (Miles Inc. Stilwell, KS) (30 μg per insect) or both, ≈2 h before treatment with 1.0 μl of the discriminating dose of the insecticide (deltamethrin, beta-cyfluthrin, propoxur, and chlorpyrifos). The discriminating dose was the LD_{99} of the tested insecticide that was generated earlier for the EHI strain (Table 2). Control cockroaches were treated with 1.0 μl of synergist, followed by acetone, whereas those cockroaches without synergist treatment were treated with acetone only.

Treated cockroaches were placed in clean petri dishes with food and water. Mortality of the cockroaches was recorded at 48 h posttreatment. For chlorpyrifos, only a few strains that showed high resistance to this insecticide were used for the synergism studies. Experiments for each insecticide, along with the synergists, were replicated five times with 10 adult males per replicate. Data were subjected to Wilcoxon sign rank test using SPSS version 12.0.1 (SPSS Inc. 2003) to determine whether percentage of mortality of the test cockroaches subjected to discriminating dose increased after synergist treatment was higher than the corresponding ones, but without synergist treatment.

Results and Discussion

The resistance levels of field populations of German cockroach from Singapore were low to very high for the pyrethroids (4.5–468.0× deltamethrin [Table 3]; 3.0–94.5× beta-cyfluthrin [Table 4]), low to high for the carbamate (3.9–21.5× propoxur [see Table 7]) and the organophosphate (1.5–22.8× chlorpyrifos [see Table 9]), absent to moderate for thephenyl pyrazole (1.0–10.0× fipronil [see Table 11]), and absent to low for the neonicotinoid (0.8–3.8× imidacloprid [see Table 12]) and the oxadiazine (1.4–5.3× indoxacarb [see Table 13]).

The majority of the field strains exhibited high to very high levels of resistance to deltamethrin (>70%) and beta-cyfluthrin (>30%) (Tables 3 and 4, respectively). The Victoria Street populations exhibited the highest level of resistance to deltamethrin (>450-fold), followed by the B1 Tampines Central (>300-fold) and Boat Quay populations (>300-fold) (Table 3). High selection pressure was exerted on these populations due to regular residual spraying of deltamethrin in these areas. Deltamethrin is the common insecticide used by pest management professionals in Singapore to control German cockroaches. Scharf et al. (1998) demonstrated that cypermethrin selection pressure applied on a *B. germanica* population for three generations increased the resistance level very quickly. Our results agree with the findings of Choo et al. (2000) in terms of prevalence of deltamethrin resistance in field populations of German cockroach in Singapore.

Very high levels of beta-cyfluthrin resistance (>85-fold) were detected in the Bt. Timah Road and Boat Quay populations (Table 4). Because deltamethrin and beta-cyfluthrin are both pyrethroids, deltamethrin resistance in these populations is likely caus-

Table 3. Toxicity of deltamethrin against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	*n*	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	200	0.2 (0.2–0.3)	0.6 (0.5–0.8)	4.2 ± 0.5	0.3 (2)	
1	Tampines Central	280	10.4 (5.8–18.8)	115.3 (48.9–844.2)	1.6 ± 0.2	13.2 (5)	52.0*
2	Thomson Plaza	240	18.9 (15.6–22.9)	56.1 (61.9–142.7)	2.5 ± 0.3	2.6 (3)	94.5*
3	Joo Chiat Road	160	13.0 (10.4–16.3)	102.0 (63.4–223.0)	1.8 ± 0.3	0.9 (4)	65.0*
4	Biopolis Street	240	17.3 (8.0–28.2)	76.1 (40.6–1007.2)	2.6 ± 0.4	2.1 (2)	86.5*
5	Tiong Baru Road	240	4.3 (3.2–5.7)	54.7 (33.2–116.1)	1.5 ± 0.2	0.7 (4)	21.5*
6	B1 Tampines Central	200	63.8 (50.1–118.3)	286.7 (141.5–2523.3)	2.5 ± 0.7	1.0 (2)	319.0*
7	Bt. Timah Road	200	21.9 (13.4–36.4)	82.6 (45.7–476.1)	2.9 ± 0.3	6.7 (3)	109.5*
8	Bt. Merah Central	280	12.4 (10.2–15.0)	74.1 (52.6–122.6)	2.1 ± 0.2	4.4 (5)	62.0*
9	Beach Road	200	17.5 (10.0–42.7)	1,143.5 (187.5–1146859.7)	0.9 ± 0.3	1.6 (2)	87.5*
10	Boat Quay	160	62.7 (51.2–97.1)	230.0 (130.6–1032.9)	2.9 ± 0.7	1.6 (2)	313.5*
11	Jalan Membina	160	22.3 (16.4–28.8)	166.9 (96.6–537.5)	1.9 ± 0.4	1.4 (2)	111.5*
12	Victoria Street	160	93.6 (71.8–173.3)	469.2 (225.0–3667.9)	2.4 ± 0.6	0.8 (2)	468.0*
13	Ang Mo Kio	160	25.4 (21.4–28.9)	68.0 (53.5–108.4)	3.8 ± 0.7	1.9 (2)	127.0*
14	Jurong	240	25.7 (21.0–32.0)	158.6 (103.6–309.9)	2.1 ± 0.3	2.5 (4)	128.5*
15	Kallang Sector Rd	200	38.6 (27.3–77.4)	578.0 (196.5–8920.4)	1.4 ± 0.3	1.5 (3)	193.0*
16	Serangoon Central	200	11.0 (6.3–14.8)	115.8 (65.2–450.0)	1.6 ± 0.4	1.7 (3)	55.0*
17	Cavenagh Road	160	36.5 (30.6–44.7)	133.8 (91.1–272.3)	2.9 ± 0.5	0.6 (2)	182.5*
18	Jelebu Road	200	5.3 (4.4–6.5)	22.8 (16.8–35.3)	2.6 ± 0.3	1.6 (4)	26.5*
19	Bedok North	160	0.9 (0.5–1.8)	3.6 (1.7–66.5)	2.7 ± 0.4	2.5 (2)	4.5*
20	Rivervale Crescent	280	2.4 (1.6–3.4)	17.4 (9.8–54.3)	1.9 ± 0.2	4.9 (4)	12.0*
21	Geylang	200	7.9 (4.5–12.5)	44.3 (23.7–219.8)	2.2 ± 0.3	4.6 (3)	39.5*
22	Ghimmoh Road	200	7.4 (4.4–11.4)	53.7 (27.5–260.0)	1.9 ± 0.3	3.5 (3)	37.0*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on non-overlap of 95% FL.

Table 4. Toxicity of β-cyfluthrin against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	120	0.2 (0.1–0.2)	0.3 (0.3–0.6)	5.1 ± 1.1	0.0 (1)	
1	Tampines Central	160	5.6 (3.0–7.4)	30.0 (20.7–71.0)	2.3 ± 0.5	1.3 (3)	28.0*
2	Thomson Plaza	120	3.6 (2.0–5.2)	41.1 (21.7–168.8)	1.6 ± 0.3	0.1 (1)	18.0*
3	Joo Chiat Road	160	11.1 (8.9–14.6)	49.7 (29.0–223.0)	2.5 ± 0.6	0.0 (1)	55.5*
4	Biopolis Street	200	6.5 (4.8–8.3)	19.0 (13.8–33.9)	3.5 ± 0.4	3.0 (3)	32.5*
5	Tiong Baru Road	200	3.5 (2.5–4.5)	21.2 (15.1–36.8)	2.1 ± 0.3	1.4 (3)	17.5*
6	B1 Tampines Central	200	4.8 (2.4–7.3)	188.8 (75.3–1444.8)	1.0 ± 0.2	1.9 (3)	24.0*
7	Bt. Timah Road	200	18.9 (16.4–21.5)	52.9 (42.2–75.2)	3.7 ± 0.5	0.9 (3)	94.5*
8	Bt. Merah Central	200	7.9 (5.1–10.4)	22.2 (15.6–54.6)	3.7 ± 0.5	4.4 (3)	39.5*
9	Beach Road	120	10.1 (8.1–12.5)	38.2 (24.8–109.7)	2.9 ± 0.6	0.0 (1)	50.5*
10	Boat Quay	200	17.9 (14.3–23.1)	129.1 (73.1–399.1)	1.9 ± 0.3	1.9 (3)	89.5*
11	Jalan Membina	160	6.0 (4.9–7.30)	24.7 (17.72–43.0)	2.7 ± 0.4	1.0 (2)	30.0*
12	Victoria Street	160	14.3 (12.30–16.2)	35.4 (28.5–52.6)	4.2 ± 0.7	1.4 (2)	71.5*
13	Ang Mo Kio	200	8.5 (6.7–10.2)	37.0 (27.1–63.1)	2.6 ± 0.4	3.0 (3)	42.5*
14	Jurong	160	9.9 (5.1–13.0)	50.7 (34.3–149.6)	2.3 ± 0.6	1.7 (2)	49.5*
15	Kallang Sector Road	200	11.3 (9.2–13.4)	48.1 (35.0–82.0)	2.6 ± 0.4	2.9 (3)	56.5*
16	Serangoon Central	200	8.6 (7.1–9.9)	25.6 (20.0–39.1)	3.5 ± 0.5	0.3 (2)	43.0*
17	Cavenagh Road	200	15.3 (12.8–17.8)	51.9 (40.0–79.7)	3.1 ± 0.4	0.6 (3)	76.5*
18	Jelebu Road	200	3.8 (3.1–4.6)	17.6 (12.8–28.8)	2.5 ± 0.3	2.3 (3)	19.0*
19	Bedok North	200	0.6 (0.4–0.7)	2.9 (2.07–5.01)	2.3 ± 0.3	2.5 (3)	3.0*
20	Rivervale Crescent	200	1.0 (0.4–2.0)	6.4 (2.96–64.9)	2.0 ± 0.2	7.1 (3)	5.0*
21	Geylang	160	2.5 (1.5–3.4)	16.9 (10.4–48.6)	2.0 ± 0.4	0.1 (1)	12.5*
22	Ghimmoh Road	120	9.4 (7.6–10.5)	17.5 (15.1–23.7)	6.1 ± 1.3	0.4 (1)	47.0*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on non-overlap of 95% FL.

ing cross-resistance to beta-cyfluthrin, as the latter was never used in any of these sites. Indeed, many cases of cross-resistance in the German cockroach have been documented (van den Heuvel and Cochran 1965, McDonald and Cochran 1968, Collins 1973, Nelson and Wood 1982, Atkinson et al. 1991, Lee et al. 1996a).

Resistance to deltamethrin and beta-cyfluthrin in the field-collected strains was reduced with PBO or DEF (Tables 5 and 6). Pretreatment of PBO or DEF caused partial negation of deltamethrin and beta-cyfluthrin resistance, which suggests the involvement of both P450 monooxygenases and esterases in pyrethroid resistance in most of these strains. All the field strains tested with deltamethrin and beta-cyfluthrin showed significant ($P < 0.05$) increase in mortality after pretreatment with PBO, whereas DEF pretreatment increased the mortality of six to eight field strains (indicating the involvement of esterases). More than

Table 5. Percentage mortality of the field-collected German cockroaches after treatment with the discriminating dose of deltamethrin (0.046 μg per insect) and synergists PBO (100 μg per insect) and DEF (30 μg per insect)

Strain	Mean % mortality ± SEM[a]			
	Deltamethrin only	Deltamethrin + PBO	Deltamethrin + DEF	Deltamethrin + PBO +DEF
EHI	100 ± 0	100 ± 0	100 ± 0	100 ± 0
Tampines Central	26 ± 4	90 ± 3*	56 ± 4*	98 ± 2*
Thomson Plaza	8 ± 4	94 ± 2*	72 ± 4*	94 ± 4*
Joo Chiat Rd.	16 ± 2	54 ± 9*	34 ± 7	88 ± 4*
Biopolis Street	0 ± 0	16 ± 4*	16 ± 2*	56 ± 5*
Tiong Baru Rd.	22 ± 4	74 ± 5*	44 ± 5*	88 ± 5*
B1 Tampines Central	16 ± 2	86 ± 5*	66 ± 6*	88 ± 4*
Bt. Timah Rd.	0 ± 0	34 ± 2*	4 ± 2	40 ± 5*
Bt. Merah Central	0 ± 0	50 ± 5*	12 ± 5	62 ± 9*
Beach Rd.	0 ± 0	16 ± 4*	8 ± 4	26 ± 4*
Boat Quay	2 ± 2	34 ± 6*	8 ± 4	36 ± 5*
Jln. Membina	2 ± 2	38 ± 4*	10 ± 4	54 ± 6*
Victoria St.	0 ± 0	26 ± 4*	12 ± 4	46 ± 7*
Ang Mo Kio	0 ± 0	46 ± 2*	10 ± 3	66 ± 7*
Jurong	14 ± 4	58 ± 5*	34 ± 2*	80 ± 4*
Kallang Sector Rd.	0 ± 0	26 ± 6*	8 ± 4	52 ± 8*
Serangoon Central	0 ± 0	54 ± 9*	10 ± 3	74 ± 7*
Cavenagh Rd.	0 ± 0	38 ± 9*	10 ± 3	64 ± 4*
Jelebu Rd.	26 ± 7	84 ± 9*	24 ± 6	86 ± 2*
Bedok North	80 ± 6	100 ± 0*	80 ± 5	100 ± 0*
Rivervale Crescent	44 ± 5	98 ± 2*	90 ± 4*	98 ± 2*
Geylang	18 ± 4	94 ± 4*	64 ± 4*	100 ± 0*
Ghimmoh Rd.	24 ± 6	88 ± 4*	50 ± 6	100 ± 0*

[a] Mean mortality with an asterisk within the same row of the same strain indicates that it is significantly different from that of deltamethrin treatment only ($P < 0.05$; Wilcoxon sign rank).

Table 6. Percentage mortality of the field-collected German cockroaches after treatment with the discriminating dose of β-cyfluthrin (0.024 μg per insect) and the synergists PBO (100 μg per insect) and DEF (30 μg per insect)

Strain	Mean % mortality ± SEM[a]			
	β-Cyfluthrin only	β-Cyfluthrin + PBO	β-Cyfluthrin + DEF	β-Cyfluthrin + PBO + DEF
EHI	100 ± 0	100 ± 0	100 ± 0	100 ± 0
Tampines Central	22 ± 2	66 ± 5*	56 ± 5*	100 ± 0*
Thomson Plaza	26 ± 4	90 ± 3*	62 ± 6*	96 ± 2*
Joo Chiat Rd.	4 ± 2	64 ± 9*	30 ± 3*	86 ± 4*
Biopolis Street	0 ± 0	40 ± 4*	2 ± 2	44 ± 2*
Tiong Baru Rd.	16 ± 5	76 ± 5*	46 ± 13	96 ± 2*
B1 Tampines Central	26 ± 5	86 ± 2*	86 ± 7*	94 ± 2*
Bt. Timah Rd.	0 ± 0	42 ± 4*	4 ± 2	34 ± 2*
Bt. Merah Central	2 ± 2	42 ± 4*	4 ± 4	46 ± 5*
Beach Rd.	0 ± 0	50 ± 5*	4 ± 2	56 ± 4*
Boat Quay	2 ± 2	36 ± 4*	6 ± 4	36 ± 5*
Jln. Membina	4 ± 2	26 ± 2*	6 ± 2	56 ± 7*
Victoria St.	0 ± 0	54 ± 10*	8 ± 4	48 ± 4*
Ang Mo Kio	2 ± 2	24 ± 2*	4 ± 4	42 ± 2*
Jurong	0 ± 0	50 ± 3*	20 ± 6	92 ± 4*
Kallang Sector Rd.	0 ± 0	36 ± 4*	2 ± 2	30 ± 3*
Serangoon Central	2 ± 2	56 ± 7*	18 ± 4	82 ± 9*
Cavenagh Rd.	0 ± 0	16 ± 4*	10 ± 3	48 ± 4*
Jelebu Rd.	22 ± 7	90 ± 5*	24 ± 2	84 ± 5*
Bedok North	50 ± 4	98 ± 2*	68 ± 5	100 ± 0*
Rivervale Crescent	40 ± 10	98 ± 2*	82 ± 5	98 ± 2*
Geylang	20 ± 3	86 ± 4*	58 ± 5*	96 ± 2*
Ghimmoh Rd.	14 ± 2	64 ± 4*	56 ± 4*	90 ± 3*

[a] Mean mortality with an asterisk within the same row of the same strain indicates that it is significantly different from that of β-cyfluthrin treatment only ($P < 0.05$; Wilcoxon sign rank).

95% mortality was achieved with a combination of both PBO and DEF along with deltamethrin or beta-cyfluthrin in B1 Tampines Central, Bedok North, Rivervale Crescent, Geylang Road, and Ghimmoh Road, as well as in Thomson Plaza and Tiong Baru Road for beta-cyfluthrin. However, PBO + DEF treatment had only limited, but significant ($P < 0.05$), impact on deltamethrin and beta-cyfluthrin resistance in a number of strains (e.g., Biopolis Street, Beach Road, Bt. Timah Road, Boat Quay, Victoria Street, Ang Mo Kio, Kallang Sector Road, and Cavenagh Road), which indicates the involvement of other resistance mechanisms (e.g., target site insensitivity [*kdr*-type]). Lee et al. (1996a) suggested the presence of *kdr*-type resistance in several field-collected strains of German cockroaches from Malaysia when PBO or DEF failed to significantly reduce to the resistance levels of cypermethrin and permethrin. Such an observation also has been noted in many pyrethroid-resistant strains of this species (Scott et al. 1990, Valles and Yu 1996, Wei et al. 2001, Pridgeon et al. 2002, Limoee et al. 2007).

Low to moderate levels of resistance to propoxur were detected in 72.7% of the field strains; 27.3% of the strains showed high resistance to propoxur, and another 59.1% demonstrated moderate resistance to propoxur (Table 7). The Beach Road population showed the highest level of resistance to propoxur. In contrast, propoxur resistance was rather prevalent in field populations of German cockroach from peninsular Malaysia, which is a result of long-term dependency on propoxur as the main insecticide used for German cockroach control in Malaysia (Lee et al. 1996a; Lee and Lee 2002, 2004).

The synergists PBO and DEF significantly ($P < 0.05$) suppressed propoxur resistance to varying degrees depending on the strain of German cockroach (Table 8). Complete negation of propoxur resistance was observed in the Thomson Plaza, Joo Chiat Road, and Bt. Timah Road populations upon PBO treatment, which indicates the involvement of P450 monooxygenase in the resistance. Propoxur resistance in the Victoria Street, Ang Mo Kio, Jelebu Road, Serangoon Central and Bedok North populations was completely negated with DEF. These results suggest the contribution of both enhanced oxidative and hydrolytic metabolism to propoxur resistance in German cockroach populations in Singapore. Sánchez-Arroyo et al. (2001) previously reported that both oxidative and hydrolytic enzymes are associated with the detoxification of propoxur.

Our findings are comparable with those of Lee et al. (1996a) and Lee and Lee (2004), who reported that propoxur resistance in the majority of German cockroach strains from Peninsular Malaysia was primarily due to elevated P450 monooxygenases and esterases. Lee and Lee (2004) also reported that altered acetylcholinesterase was involved in propoxur resistance in several field strains of German cockroach from Peninsular Malaysia, as the resistance levels were only partially suppressed with PBO and DEF. In this study, the administration of PBO + DEF along with propoxur led to complete mortality in all of the field strains tested (except for 98% in the B1 Tampines Central population) (Table 8). This finding ruled out the possibility of modified acetylcholinesterase as a resistance mechanism for propoxur in German cockroaches from Singapore. In fact, altered acetylcholinesterase is not

Table 7. Toxicity of propoxur against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	280	4.6 (4.1–5.2)	15.5 (11.8–23.8)	3.1 ± 0.4	3.6 (5)	—
1	Tampines Central	200	52.5 (35.8–93.4)	360.7 (159.0–5106.9)	2.0 ± 0.3	3.3 (3)	11.4*
2	Thomson Plaza	200	36.1 (29.9–43.4)	163.7 (115.1–291.7)	2.5 ± 0.3	1.5 (3)	7.8*
3	Joo Chiat Road	200	33.5 (26.0–46.3)	112.4 (71.4–306.2)	3.1 ± 0.4	2.2 (2)	7.3*
4	Biopolis Street	160	19.3 (7.4–36.6)	122.1 (54.9–3566.8)	2.1 ± 0.3	2.2 (2)	4.2*
5	Tiong Baru Road	160	24.7 (20.0–30.0)	105.4 (74.1–194.1)	2.6 ± 0.4	1.8 (2)	5.4*
6	B1 Tampines Central	200	34.6 (23.5–49.0)	105.8 (68.0–333.8)	3.4 ± 0.4	5.5 (3)	7.5*
7	Bt. Timah Road	200	43.9 (35.1–56.9)	306.9 (177.9–853.9)	2.0 ± 0.3	2.4 (3)	9.5*
8	Bt. Merah Central	200	31.2 (18.6–47.6)	96.8 (58.9–522.3)	2.8 ± 0.4	7.1 (3)	6.8*
9	Beach Road	240	98.9 (83.6–129.2)	358.7 (228.8–908.2)	2.9 ± 0.5	2.3 (3)	21.5*
10	Boat Quay	160	39.3 (34.1–45.7)	100.7 (78.7–151.7)	4.0 ± 0.6	1.3 (2)	8.5*
11	Jalan Membina	200	18.1 (15.0–21.7)	73.8 (55.0–114.6)	2.7 ± 0.3	0.8 (6)	3.9*
12	Victoria Street	160	31.8 (26.9–36.9)	77.6 (61.4–116.6)	4.2 ± 0.7	0.8 (1)	6.9*
13	Ang Mo Kio	240	26.3 (20.0–36.8)	91.8 (57.6–249.4)	3.0 ± 0.3	6.4 (4)	5.7*
14	Jurong	200	66.6 (54.1–84.4)	412.7 (237.2–1367.2)	2.1 ± 0.4	1.4 (3)	14.5*
15	Kallang Sector Road	200	59.1 (47.1–82.0)	388.8 (212.8–1266.3)	2.0 ± 0.3	1.1 (3)	12.8*
16	Serangoon Central	160	18.7 (14.7–22.8)	73.7 (54.8–117.3)	2.8 ± 0.4	0.4 (2)	4.1*
17	Cavenagh Road	200	60.4 (51.0–72.9)	261.5 (173.9–568.8)	2.6 ± 0.4	2.8 (3)	13.1*
18	Jelebu Road	160	25.7 (20.3–31.9)	120.2 (83.9–219.0)	2.5 ± 0.4	0.3 (2)	5.6*
19	Bedok North	160	23.1 (18.5–27.8)	83.7 (62.4–135.1)	2.9 ± 0.4	0.3 (2)	5.0*
20	Rivervale Crescent	160	24.4 (16.7–30.0)	90.7 (64.7–201.8)	2.9 ± 0.7	1.0 (1)	5.3*
21	Geylang	200	26.8 (16.9–37.7)	127.2 (75.7–465.1)	2.4 ± 0.3	3.7 (3)	5.8*
22	Ghimmoh Road	200	86.5 (71.3–119.9)	373.3 (219.1–1178.4)	2.6 ± 0.5	2.6 (2)	18.8*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on nonoverlap of 95% FL.

commonly reported in the German cockroach (Siegfried and Scott 1992).

Low resistance to chlorpyrifos was recorded in >70% of the strains, whereas 18.2% of the strains showing moderate levels of resistance (Table 9). Only two strains (the Boat Quay and Cavenagh Road populations) exhibited high resistance to chlorpyrifos. A mixed level of synergism was found with the pretreatment of PBO among the six field strains selected for the chlorpyrifos synergism study (Table 10). This is probably due to PBO inhibits the bioactivation of chlorpyrifos to chlorpyrifos-oxon. Complete elimination of chlorpyrifos resistance also occurred with the cotreatment of PBO + DEF and chlorpyrifos. Although the results suggest that esterases play a major role in chlorpyrifos resistance, the involvement of P450 monooxygenases was also documented in this study. Joo Chiat Road, Boat Quay, and Cavenagh Road

Table 8. Percentage mortality of the field-collected German cockroaches after treatment with the discriminating dose of propoxur (1.347 μg per insect) and the synergists PBO (100 μg per insect) and DEF (30 μg per insect)

Strain	Mean % mortality ± SEM[a]			
	Propoxur only	Propoxur + PBO	Propoxur + DEF	Propoxur + PBO + DEF
EHI	100 ± 0	100 ± 0	100 ± 0	100 ± 0
Tampines Central	22 ± 4	94 ± 4*	86 ± 6*	100 ± 0*
Thomson Plaza	32 ± 7	100 ± 0*	94 ± 2*	100 ± 0*
Joo Chiat Rd.	46 ± 2	100 ± 0*	96 ± 2*	100 ± 0*
Biopolis Street	58 ± 5	96 ± 2*	94 ± 4*	100 ± 0*
Tiong Baru Rd.	44 ± 7	98 ± 2*	96 ± 2*	100 ± 0*
B1 Tampines Central	48 ± 6	92 ± 4*	96 ± 2*	98 ± 2*
Bt. Timah Rd.	48 ± 6	100 ± 0*	86 ± 2*	100 ± 0*
Bt. Merah Central	38 ± 6	92 ± 4*	96 ± 2*	100 ± 0*
Beach Rd.	14 ± 5	54 ± 7*	76 ± 8*	100 ± 0*
Boat Quay	24 ± 4	86 ± 5*	80 ± 5*	100 ± 0*
Jln. Membina	52 ± 5	86 ± 2*	98 ± 2*	100 ± 0*
Victoria St.	36 ± 6	90 ± 4*	100 ± 0*	100 ± 0*
Ang Mo Kio	44 ± 4	98 ± 2*	100 ± 0*	100 ± 0*
Jurong	14 ± 4	76 ± 2*	90 ± 3*	100 ± 0*
Kallang Sector Rd.	6 ± 2	76 ± 9*	64 ± 4*	100 ± 0*
Serangoon Central	54 ± 2	86 ± 6*	100 ± 0*	100 ± 0*
Cavenagh Rd.	10 ± 5	80 ± 8*	84 ± 7*	100 ± 0*
Jelebu Rd.	46 ± 6	90 ± 4*	100 ± 0*	100 ± 0*
Bedok North	38 ± 2	96 ± 4*	100 ± 0*	100 ± 0*
Rivervale Crescent	44 ± 4	94 ± 4*	98 ± 2*	100 ± 0*
Geylang	34 ± 5	90 ± 4*	98 ± 2*	100 ± 0*
Ghimmoh Rd.	22 ± 4	78 ± 7*	88 ± 4*	100 ± 0*

[a] Mean mortality with an asterisk within the same row of the same strain indicates that it is significantly different from that of propoxur treatment only ($P < 0.05$; Wilcoxon sign rank).

Table 9. Toxicity of chlorpyrifos against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	200	4.4 (3.2–6.2)	11.1 (7.4–48.2)	4.1 ± 0.5	6.2 (3)	
1	Tampines Central	240	10.7 (8.6–14.5)	24.8 (17.0–103.4)	4.5 ± 0.6	10.4 (4)	2.4*
2	Thomson Plaza	160	7.4 (6.5–8.3)	13.5 (11.7–16.0)	6.3 ± 0.9	0.3 (1)	1.7*
3	Joo Chiat Road	160	28.3 (24.3–33.0)	71.8 (57.1–101.2)	4.1 ± 0.5	0.7 (2)	6.4*
4	Biopolis Street	240	11.4 (9.8–13.4)	25.9 (19.8–46.1)	4.6 ± 0.6	5.2 (4)	2.6*
5	Tiong Baru Road	240	20.7 (16.3–26.7)	204.3 (112.8–610.1)	1.7 ± 0.3	1.0 (4)	4.7*
6	B1 Tampines Central	200	27.4 (18.5–36.3)	216.2 (135.1–519.0)	1.8 ± 0.3	2.0 (2)	6.2*
7	Bt. Timah Road	240	13.7 (10.9–17.3)	33.0 (23.4–89.3)	4.3 ± 0.6	8.2 (4)	3.1*
8	Bt. Merah Central	240	6.6 (5.2–8.0)	17.0 (12.9–30.7)	4.0 ± 0.5	5.6 (4)	1.5
9	Beach Road	200	13.6 (12.5–14.7)	26.2 (22.2–34.9)	5.8 ± 0.9	0.9 (3)	3.1*
10	Boat Quay	200	100.2 (78.5–147.6)	197.3 (138.5–927.2)	5.6 ± 0.7	7.6 (3)	22.8*
11	Jalan Membina	160	28.1 (24.4–32.3)	74.5 (59.0–108.3)	3.9 ± 0.5	1.9 (2)	6.4*
12	Victoria Street	200	30.2 (26.5–35.2)	92.0 (69.6–144.1)	3.4 ± 0.4	0.3 (3)	6.9*
13	Ang Mo Kio	240	7.9 (5.5–10.0)	18.4 (13.0–73.8)	4.5 ± 0.6	10.4 (4)	1.8
14	Jurong	200	19.6 (17.6–22.2)	46.9 (37.3–68.6)	4.3 ± 0.6	2.7 (3)	4.5*
15	Kallang Sector Road	200	19.8 (17.2–23.6)	66.3 (47.1–122.7)	3.1 ± 0.5	1.5 (3)	4.5*
16	Serangoon Central	200	8.1 (7.4–8.8)	16.1 (14.0–20.0)	5.5 ± 0.6	1.4 (3)	1.8*
17	Cavenagh Road	200	52.4 (41.9–70.3)	294.2 (177.9–691.3)	2.2 ± 0.3	0.5 (3)	11.9*
18	Jelebu Road	160	9.6 (7.1–12.8)	19.0 (13.8–78.6)	5.6 ± 0.8	2.4 (2)	2.2*
19	Bedok North	160	8.6 (7.9–9.4)	16.9 (14.6–21.4)	5.6 ± 0.8	2.6 (3)	2.0*
20	Rivervale Crescent	200	13.3 (11.7–15.1)	38.4 (29.3–62.7)	3.6 ± 0.6	1.8 (3)	3.0*
21	Geylang	200	10.0 (8.6–11.4)	17.3 (14.3–27.3)	6.9 ± 0.9	3.7 (3)	2.3*
22	Ghimmoh Road	160	16.9 (15.3–20.0)	36.3 (27.3–71.6)	5.0 ± 1.1	0.7 (2)	3.8*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on nonoverlap of 95% FL.

strains showed significant ($P < 0.05$) increase in percentage of mortality to chlopyrifos treatment after pretreatment with PBO. Previously, Scharf et al. (1999) demonstrated that overexpression of P450 monooxygenases was well correlated with chlorpyrifos resistance in *B. germanica.* The involvement of microsomal oxidases and hydrolases in chlorpyrifos resistance also has been documented in several strains of German cockroach (Siegfried and Scott 1992, Hemingway et al. 1993, Lee and Lee 2004). A more detailed synergism study on chlorpyrifos resistance is warranted to further substantiate the current observation.

Unlike previously recorded in the United States (Rust and Reierson 1991), the lower prevalence and level of chlorpyrifos resistance in field populations of German cockroaches from Singapore is probably due to the fact that chlorpyrifos is not the primary choice of residual insecticide. Resistance to chlorpyrifos was also not rampant in German cockroaches of Peninsular Malaysia (Lee et al. 1996a, 1999; Lee and Lee 2002), as organophosphate insecticides are less favored by the pest control industry because of their stronger odor when compared with pyrethroids (Lee and Lee 2004).

In some parts of the world, chlorpyrifos resistance in the German cockroach is significant but insufficient to cause serious control failure; therefore, it continues to be used for German cockroach control (Spencer et al. 1999). In Malaysia, this compound is often used in food preparation outlets that have serious infestation of pyrethroid-resistant German cockroaches. For strains with high resistance levels to both pyrethroids and organophosphate (e.g., the Boat Quay and Cavenagh Road populations), an alternative control strategy might be necessary. Organophosphate insecticides are not effective for German cockroach control when a resistance ratio of >10 is present (based on topical applications; Ballard et al. 1984, Rust and Reierson 1991).

Of the 22 strains tested with fipronil, only four strains showed significantly higher level of tolerance to this compound compared with the susceptible strain (Table 11). The B1 Tampines Central (3.0×)

Table 10. Percentage mortality of selected field-collected German cockroach strains after treatment with the discriminating dose of chlorpyrifos (0.867 μg per insect) and the synergists PBO (100 μg per insect) and DEF (30 μg per insect)

Strain	Mean % mortality ± SEM[a]			
	Chlorpyrifos only	Chlorpyrifos + PBO	Chlorpyrifos + DEF	Chlorpyrifos + PBO + DEF
EHI	100 ± 0	100 ± 0	100 ± 0	100 ± 0
Joo Chiat Rd.	46 ± 5	66 ± 5*	100 ± 0*	100 ± 0*
B1 Tampines Central	68 ± 4	72 ± 7	100 ± 0*	100 ± 0*
Boat Quay	4 ± 2	32 ± 2*	100 ± 0*	100 ± 0*
Jln. Membina	50 ± 5	72 ± 6	100 ± 0*	100 ± 0*
Victoria St.	60 ± 3	78 ± 6	100 ± 0*	100 ± 0*
Cavenagh Rd.	24 ± 2	64 ± 8*	100 ± 0*	100 ± 0*

[a] Mean mortality with an asterisk within the same row of the same strain indicates that it is significantly different from that of chlorpyrifos treatment only ($P < 0.05$; Wilcoxon sign rank).

Table 11. Toxicity of fipronil against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	280	0.1 (0.0–0.1)	0.1 (0.1–0.1)	6.3 ± 1.0	0.8 (1)	
1	Tampines Central	240	0.1 (0.1–0.1)	0.2 (0.1–0.3)	6.1 ± 0.7	13.6 (4)	1.0
2	Thomson Plaza	240	0.1 (0.1–0.1)	0.2 (0.1–0.2)	4.8 ± 0.7	0.2 (2)	1.0
3	Joo Chiat Road	240	0.1 (0.1–0.1)	0.2 (0.2–0.4)	4.1 ± 0.6	4.9 (4)	1.0
4	Biopolis Street	240	0.1 (0.1–0.1)	0.2 (0.2–0.3)	4.4 ± 0.5	1.6 (2)	1.0
5	Tiong Baru Road	240	0.1 (0.1–0.1)	0.2 (0.1–0.2)	5.2 ± 0.6	2.2 (4)	1.0
6	B1 Tampines Central	240	0.3 (0.2–0.4)	2.0 (1.3–4.1)	1.9 ± 0.3	1.0 (4)	3.0*
7	Bt. Timah Road	200	0.1 (0.1–0.1)	0.1 (0.1–0.2)	6.3 ± 0.9	0.2 (1)	1.0
8	Bt. Merah Central	240	0.1 (0.1–0.1)	0.1 (0.1–0.2)	5.6 ± 0.7	4.5 (3)	1.0
9	Beach Road	280	0.1 (0.1–0.1)	0.2 (0.1–0.2)	4.7 ± 0.6	1.5 (2)	1.0
10	Boat Quay	280	0.1 (0.1–0.2)	0.7 (0.4–3.0)	2.4 ± 0.4	5.0 (4)	1.0
11	Jalan Membina	160	0.1 (0.1–0.1)	0.4 (0.3–0.7)	3.4 ± 0.6	0.9 (2)	1.0
12	Victoria Street	240	0.2 (0.1–0.3)	2.5 (1.4–8.2)	1.5 ± 0.3	2.6 (3)	2.0
13	Ang Mo Kio	240	0.1 (0.1–0.1)	0.2 (0.1–0.2)	6.2 ± 0.7	1.2 (4)	1.0
14	Jurong	280	0.2 (0.2–0.3)	1.1 (0.8–2.0)	2.3 ± 0.3	2.5 (5)	2.0*
15	Kallang Sector Road	200	0.1 (0.1–0.1)	0.1 (0.1–0.2)	9.3 ± 1.6	1.4 (2)	1.0
16	Serangoon Central	240	0.1 (0.1–0.1)	0.1 (0.1–0.2)	6.0 ± 0.7	3.1 (3)	1.0
17	Cavenagh Road	240	0.8 (0.8–1.0)	2.6 (2.0–4.2)	3.4 ± 0.5	1.9 (4)	8.0*
18	Jelebu Road	200	0.1 (0.1–0.1)	0.1 (0.1–0.2)	6.9 ± 0.9	1.9 (3)	1.0
19	Bedok North	200	0.1 (0.1–0.1)	0.1 (0.1–0.1)	7.0 ± 0.9	1.7 (2)	1.0
20	Rivervale Crescent	240	0.1 (0.1–0.1)	0.1 (0.1–0.2)	7.2 ± 0.8	1.6 (4)	1.0
21	Geylang	240	0.1 (0.1–0.1)	0.1 (0.1–0.2)	7.2 ± 0.9	2.2 (2)	1.0
22	Ghimmoh Road	240	1.0 (0.9–1.1)	2.2 (1.8–3.1)	4.6 ± 0.6	3.8 (4)	10.0*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on nonoverlap of 95% FL.

and Jurong (2.0×) populations showed low resistance to fipronil, and the Cavenagh Road (8.0×) and Ghimmoh Road (10.0×) populations showed moderate resistance. Fipronil has been reported to provide satisfactory control of insect pests at an extremely low concentration and to be effective against insects resistant to conventional insecticides. Fipronil works by blocking chloride ion flow through GABA-regulated chloride channels (Gant et al. 1998, Zhao et al. 2003), and this unique mode of action has been explored to control insecticide-resistant German cockroaches (Lee and Ng 2009). Fipronil is highly toxic to German cockroaches (Kaakeh et al. 1997a, Scott and Wen 1997, Valles et al. 1997), effective even in nanogram quantities, and is more toxic than organophosphates (Kaakeh et al. 1997a).

The mode of action of fipronil closely resembles that of dieldrin (Hosie et al. 1995, Gant et al. 1998). We currently are unable to discern whether the fipronil resistance in the four strains recorded in this study was due to selection pressure by the fipronil gel bait, to selection by dieldrin that occurred three decades ago, or both. Holbrook et al. (2003) confirmed that German cockroach strains that were resistant to cyclodiene were cross-resistant to fipronil. Kristensen et al. (2005) found fipronil resistance in dieldrin-resistant Danish populations of *B. germanica* that had never been exposed to fipronil and demonstrated the involvement of *Rdl* mutation. Although they found variation between the degrees of dieldrin and fipronil resistance in the evaluated strains, they attributed that the difference was due to differential action of the two insecticides on GABA-gated chloride channels.

Only five strains (Boat Quay, Victoria Street, Cavenagh Road, Jelebu Road and Ghimmoh Road) showed higher tolerance to imidacloprid compared with the susceptible strain (Table 12). Imidacloprid is an agonist of insect nicotinic acetylcholine receptors, and it has high selective toxicity for insects over vertebrates (Matsuda et al. 2001, Nauen et al. 2001). Kaakeh et al. (1997b) described the knockdown effect of topically applied imidacloprid as rapid and transient. In fact, in this study we observed that cockroaches were immobilized within an hour of treatment but managed to recover after 48 or 72 h, with a higher recovery rate in the field-collected strains compared with the susceptible strain. Previously, Wen and Scott (1997) and Wei et al. (2001) reported cross-resistance to imidacloprid in a German cockroach strain showing P450 monooxygenase-based resistance. Because the RR_{50} to imidacloprid detected was relatively low (<4) in this study, it is difficult to ascertain whether these strains possess natural tolerance to imidacloprid, or due to cross-resistance.

Indoxacarb resistance was absent to low (1.4–5.3×) in field populations of German cockroaches from Singapore (Table 13). The RR_{50} values ranged from 1.4 and 5.3×, with the Cavenagh Road strain displaying the highest tolerance level. Indoxacarb is an oxadiazine insecticide with a mode of action that is distinct from other commercial insecticides (Lapied et al. 2001). Indoxacarb requires bioactivation by the target insect into *N*-decarbomethoxyllated S-metabolite (DCJW), which are highly potent voltage-dependent inhibitors of the sodium channel (Wing et al. 1998). DCJW is more insecticidally active than the parent compound (indoxacarb) due to their irreversible block of the sodium channel (Zhao et al. 2005).

Because both indoxacarb and the pyrethroids target insect voltage-dependent sodium channels (although their specific modes of actions are not entirely similar; Lapied et al. 2001), low cross-resistance in *kdr*-resistant insects is possible. On the contrary with this study, resistance to indoxacarb has yet to be documented

Table 12. Toxicity of imidacloprid against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	160	25.3 (20.0–31.9)	134.4 (88.1–279.5)	2.3 ± 0.3	0.8 (2)	
1	Tampines Central	160	28.7 (21.0–38.1)	253.8 (141.2–803.7)	1.7 ± 0.3	1.0 (2)	1.1
2	Thomson Plaza	160	37.3 (23.8–53.7)	647.4 (316.3–2556.5)	1.3 ± 0.2	1.6 (2)	1.5
3	Joo Chiat Road	160	30.9 (23.3–40.6)	238.5 (138.3–666.5)	1.9 ± 0.3	0.9 (2)	1.2
4	Biopolis Street	160	36.7 (29.3–46.9)	191.8 (122.9–413.6)	2.3 ± 0.3	1.6 (2)	1.5
5	Tiong Baru Road	200	34.9 (27.2–44.9)	232.4 (154.1–442.0)	2.0 ± 0.3	2.7 (3)	1.4
6	B1 Tampines Central	160	29.3 (22.1–38.8)	235.7 (133.3–701.6)	1.8 ± 0.3	0.5 (2)	1.2
7	Bt. Timah Road	160	39.7 (25.3–54.7)	500.7 (258.9–2033.9)	1.5 ± 0.3	1.0 (2)	1.6
8	Bt. Merah Central	160	27.3 (20.9–35.6)	191.5 (113.8–501.3)	1.9 ± 0.3	1.4 (2)	1.1
9	Beach Road	160	27.2 (19.7–36.3)	249.6 (136.9–828.1)	1.7 ± 0.3	0.6 (2)	1.1
10	Boat Quay	160	61.0 (45.8–92.1)	498.1 (246.6–2026.3)	1.8 ± 0.3	1.9 (2)	2.4*
11	Jalan Membina	200	20.0 (13.4–27.0)	229.4 (136.6–571.4)	1.6 ± 0.2	1.5 (3)	0.8
12	Victoria Street	200	46.4 (32.7–66.5)	911.7 (410.2–4151.6)	1.3 ± 0.2	0.8 (3)	1.8*
13	Ang Mo Kio	160	35.5 (27.6–47.7)	246.1 (141.3–684.6)	2.0 ± 0.3	0.5 (2)	1.4
14	Jurong	160	31.3 (22.8–42.8)	325.2 (167.4–1267.5)	1.6 ± 0.3	1.1 (2)	1.2
15	Kallang Sector Road	160	25.0 (19.2–32.0)	158.0 (99.2–363.9)	2.1 ± 0.3	1.8 (2)	1.0
16	Serangoon Central	160	29.0 (21.7–39.1)	255.6 (138.8–842.4)	1.7 ± 0.3	2.0 (2)	1.2
17	Cavenagh Road	200	81.0 (54.4–117.9)	1975.5 (894.7–8263.9)	1.2 ± 0.2	2.8 (3)	3.2*
18	Jelebu Road	200	50.8 (35.4–73.9)	1125.7 (483.2–5809.3)	1.2 ± 0.2	0.2 (3)	2.0*
19	Bedok North	160	19.5 (13.6–25.8)	173.4 (100.0–515.3)	1.7 ± 0.3	1.9 (2)	0.8
20	Rivervale Crescent	160	25.0 (17.8–33.6)	252.7 (134.8–909.5)	1.6 ± 0.3	1.1 (2)	1.0
21	Geylang	160	35.7 (27.5–44.6)	151.4 (102.1–331.3)	2.6 ± 0.5	0.6 (1)	1.4
22	Ghimmoh Road	200	95.6 (72.4–128.5)	898.7 (523.9–2137.5)	1.7 ± 0.2	1.2 (3)	3.8*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on nonoverlap of 95% FL.

earlier in the German cockroach, although other reports have shown indoxacarb resistance in other pests such as house fly, *Musca domestica* (L.) (Sugiyama et al. 2001, Shono et al. 2004); obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Smirle et al. 2002); diamondback moth, *Plutella xylostella* (L.) (Zhao et al. 2006); and the cutworm *Spodoptera litura* (F.) (Sayyed et al. 2008).

Typically, resistance ratios generated using the topical application method are higher than those using the tarsal contact method (Zhai and Robinson 1992, Scharf et al. 1995, Choo et al. 2000, Ladonni 2001) and should be used when the results from the tarsal contact method disagree with empirical observations (Milio et al. 1987). Zhai and Robinson (1992) reported that the topical application method is a more sensitive way to measure resistance. The surface contact (jar test) method is affected by behavioral and morphological factors, such as the movement behavior of insects, which may influence the actual amount of insecticides that is picked up by the insect's tarsal pads.

Scott et al. (1986) reported that a DDT-resistant strain of German cockroach showed a different resis-

Table 13. Toxicity of indoxacarb against field-collected strains of German cockroaches from Singapore at 48 h posttreatment

No.	Strain	n	LD_{50} (95% FL) (μg/g)	LD_{95} (95% FL) (μg/g)	Slope	χ^2 (df)	RR_{50}[a]
0	EHI	160	6.0 (4.1–8.2)	56.3 (34.5–126.7)	1.7 ± 0.3	1.6 (2)	—
1	Tampines Central	160	14.9 (11.1–19.7)	110.0 (67.2–254.6)	1.9 ± 0.3	1.2 (2)	2.5*
2	Thomson Plaza	160	8.3 (5.8–11.3)	82.7 (48.9–201.5)	1.7 ± 0.2	0.5 (2)	1.4
3	Joo Chiat Road	160	10.5 (8.0–13.3)	51.1 (36.1–87.9)	2.4 ± 0.3	0.2 (2)	1.8
4	Biopolis Street	200	15.6 (12.4–19.7)	97.8 (62.6–209.1)	2.1 ± 0.3	2.5 (3)	2.6*
5	Tiong Baru Road	160	12.7 (9.9–16.0)	86.0 (55.9–175.3)	2.0 ± 0.3	2.6 (3)	2.1*
6	B1 Tampines Central	160	14.6 (11.3–17.8)	52.1 (37.3–99.9)	3.0 ± 0.5	0.1 (1)	2.4*
7	Bt. Timah Road	200	14.6 (11.4–18.6)	105.0 (65.2–237.0)	1.9 ± 0.3	1.8 (3)	2.4*
8	Bt. Merah Central	160	12.3 (8.7–15.5)	54.5 (37.0–123.6)	2.5 ± 0.5	0.1 (1)	2.1*
9	Beach Road	200	16.7 (13.5–20.4)	80.4 (55.1–152.4)	2.4 ± 0.4	0.4 (3)	2.8*
10	Boat Quay	200	17.5 (13.8–22.5)	123.1 (75.0–292.6)	1.9 ± 0.3	1.1 (3)	2.9*
11	Jalan Membina	160	17.4 (10.7–28.4)	83.6 (43.1–785.7)	2.4 ± 0.4	4.7 (3)	2.9*
12	Victoria Street	160	10.8 (8.1–14.2)	73.8 (47.3–151.8)	2.0 ± 0.3	1.5 (2)	1.8
13	Ang Mo Kio	160	16.7 (13.3–20.8)	87.0 (54.0–239.5)	2.3 ± 0.4	0.9 (2)	2.8*
14	Jurong	160	12.4 (8.1–15.8)	54.5 (37.5–124.7)	2.6 ± 0.5	0.0 (1)	2.1
15	Kallang Sector Road	200	16.1 (12.7–20.4)	101.8 (64.3–224.4)	2.1 ± 0.3	2.4 (3)	2.7*
16	Serangoon Central	200	11.4 (9.0–14.0)	63.1 (43.2–117.0)	2.2 ± 0.3	2.8 (3)	1.9*
17	Cavenagh Road	160	31.5 (24.3–46.1)	179.7 (95.6–758.3)	2.2 ± 0.5	0.2 (1)	5.3*
18	Jelebu Road	160	10.0 (7.0–13.6)	100.0 (58.5–248.2)	1.6 ± 0.2	1.3 (2)	1.7
19	Bedok North	160	12.0 (9.2–15.1)	59.4 (40.9–109.0)	2.4 ± 0.3	0.3 (2)	2.0*
20	Rivervale Crescent	160	11.6 (8.8–14.9)	68.1 (45.2–132.0)	2.1 ± 0.3	1.2 (2)	1.9*
21	Geylang	160	11.4 (5.1–16.2)	108.6 (57.2–763.3)	1.7 ± 0.5	0.7 (1)	1.9
22	Ghimmoh Road	160	11.3 (8.4–14.8)	78.4 (49.4–169.1)	2.0 ± 0.3	0.5 (2)	1.9*

[a] Asterisk denotes that its insecticide susceptibility is significantly different from that of the susceptible strain based on nonoverlap of 95% FL.

tance profile in response to various pyrethroids when tested using the topical application and the surface contact method. They also found that the location of topical application (heads, legs, or abdomen) did not significantly affect the levels of resistance to pyrethroids. Milio et al. (1987) stated that for detection of organophosphate resistance, topical application is more suitable than the jar test method. The use of exceedingly high doses of insecticide in jar tests may result in failure to detect resistance, as the effects of detoxifying enzymes are nullified (Cochran 1997). Scharf et al. (1995) recommended the use of tarsal pad application for the evaluation of chlorpyrifos resistance as well as other insecticides that have a similar mode of action, but this method can be very labor-intensive. In this study, we used the topical application method, because the amount of insecticide applied to each insect is standardized throughout the test (Scott et al. 1990).

RR values generated from laboratory experiments have been used to predict field performance of insecticides and potential control failure. Cochran (1996) reported that a time–mortality resistance ratio of >3.0 is an indication of possible control failure in the field. Rust et al. (1993) showed that German cockroach strains with an RR of >10 to chlorpyrifos by topical application also performed poorly in choice-box tests. Rust and Reierson (1978) concluded that $14\times$ resistance to diazinon and $3.4\times$ resistance to bendiocarb in a population of German cockroach was responsible for reduced efficacy of these chemicals in the field.

Cochran (1989) stressed that although insecticide resistance is prevalent in the German cockroach, adequate control can still be achieved with the judicious selection of suitable insecticides. Koehler and Patterson (1988) managed to suppress a field population of a multiresistant (organophosphate, carbamate, and chlorinated hydrocarbon) strain of German cockroach by using residual cypermethrin and microencapsulated chlorpyrifos. Wei et al. (2001) suggested the use of fipronil to control a strain of German cockroach that was highly resistant to pyrethroid and cross-resistant to imidacloprid, because no cross-resistance to fipronil was detected.

In summary, most of the field populations of German cockroaches collected and tested in this study were found to be resistant to deltamethrin, beta-cyfluthrin, and propoxur. Chlorpyrifos resistance was still relatively low for some of the populations. Based on the results of our synergism studies, both P450 monooxygenase and esterases are probably involved in pyrethroid and carbamate resistance. It is important to note that the results obtained from this laboratory study only suggest the possible presence of insecticide resistance development in the field populations; our results do not indicate total control failure of the insecticides used in the field. Only when control failure is similarly experienced in the field can such a statement be made.

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