Sociobiology 60(4): 453-458 (2013) DOI: 10.13102/sociobiology.v60i4.453-458

Sociobiology
An international journal on social insects

RESEARCH ARTICLE - TERMITES

Evaluation of formic acid toxicity to subterranean termite, *Reticulitermes chinensis* Snyder

YJ Xie, Q Du, QY Huang, CL Lei

Huazhong Agricultural University, Wuhan, China.

Article History

Edited by
Alexandre Vasconcellos, UFPB, Brazil
Received 02 April 2013
Initial acceptance 19 May 2013
Final acceptance 18 June 2013

Keywords: Formic acid; contact toxicity; fumigation toxicity

Corresponding author
Chao Liang Lei
Hubei Insect Resources Utilization and Sust. Pest Manag. Key Laboratory
Huazhong Agricultural University,
Wuhan 430070, China
E-Mail: cl_lei@yahoo.com.cn
ioir@mail.hzau.edu.cn

Abstract

This study examined formic acid contact and fumigation toxicity to *Reticulitermes chinensis* in the laboratory. In the contact toxicity bioassay, the LD_{50} values ranged from 267.86 to 287.68 μg adult^{-1} for workers, 279.09 μg adult^{-1} for alates (male and female) and 223.08 μg adult^{-1} for soldiers after 24 h, respectively. In the fumigation bioassays, the LC_{50} values ranged from 0.84 to 1.08 μg ml^{-1} for workers, 1.19 μg ml^{-1} for alates (male and female) and 0.57 μg ml^{-1} for soldiers after 24 h, respectively. At the concentration of 2.50 μg ml^{-1}, the KT_{50} value of formic acid ranged from 25.38 to 34.75 min for workers, from 42.21 to 45.62 min for alates (male and female), from 32.18 to 36.37 min for soldiers. Although formic acid was significantly less toxic to subterranean termite than bifenthrin, but higher toxic to many other pest insects. The findings of this study provide important confirmation of formic acid with fumigation toxicity against termite. It may be worth investigating the use of formic acid for managing subterranean termite.

Introduction

Formic acid is the simplest organic acid, present in many organisms. It is found in most plant species, including *Polygonum hydropiper*, *Urttca dioica*, *Urtica urens* (Hutchens 1992, Chopra & Chopra 2006, Rahmatullah et al. 2010). In animal, formic acid is the major component of ants from the subfamily Formicinae. The produced formic acid concentration in such ant produced substances can reach up to 54% (Hölldobler & Wilson 1990). Formic acid also occurs in carabid beetles (Will et al. 2010, Rossini et al. 1997, Attygalle et al. 1992) and notodontid caterpillars (Weatherston et al. 1979, Attygalle et al. 1993).

Formic acid was reported to possess significant insecticidal activity. It has been used as a fumigant to control the varroa mite, *Varroa destructor* Anderson (Sharma et al. 1983, Underwood & Currie 2004, 2005, 2007, vanEngelsdorp et al. 2008, Calderone 2010, Giovenazzo & Dubreuil 2011), and the tracheal mite, *Acarapis woodi* Rennie (Hoppe et al. 1989, Wilson et al. 1993, Nelson et al. 1994), and red imported fire ants, *Solenopsis invicta* Buren (Chen et al. 2012), and stored product insects, *Sitophilus oryzae* and *Rhyzopertha dominica* (Chaskopoulou 2007), and the mosquito larvicidal, *Culex quinquefasciatus* and *Aedes aegypti* (Welling & Paterson 1985), and *Drosophila* and houseflies (Song & Scharf 2008a, b, 2009).

Termites are world-wide pests threatening agriculture and the urban environment (Verma et al. 2009) worldwide. They cause over 3 billion dollars worth of damage to wooden structures annually throughout the U.S. (Su & Scheffrahn 1998). Control and repair costs due to termites in China, have been increasing annually. *Reticulitermes chinensis* Snyder (Isoptera: Rhinotermitidae) is a species of termites with broad distribution that damages the wooden structures of buildings and the xylems of living old trees in China (Wei et al. 2007). Over the past two decades, the control of termite was usually accomplished by using organochlorines and organophosphates, which have been banned owing to environmental and human health concerns (Potter 1997). At the present time, several termiticides, including bifenthrin, chlorfenapyr, cyper-

ISSN: 0361-6525

methrin, fipronil, imidacloprid and permethrin, were registered for termite control around the world (UNEP Report 2000). However, the persistent use of synthetic chemicals to control termites raises several concerns related to environment and human health. In order to reduce the negative impact of pesticides on the environment and to minimize the development of insecticide resistance in target pest species, as a result, the search for good efficacy and environmentally friendly insecticide is essential. As a safer or 'green' alternative, plant derived compounds have been used in termite management as contact insecticides or repellents, such as β-Thujaplicin, Thujopsene, T-muurolol, Cinnamaldehyde and Nootkatone (Nakashima & Shimizu 1972, Yoshida et al. 1998, Maistrello et al. 2001, Chang & Cheng 2002, Cheng et al. 2004). Another potential source of natural toxins against termite is the defensive/offensive chemicals in ants. Some genus such as *Leptogenys*, *Centromyrmex*, *Termitopone*, *Megaponera* and *Pheidole* are all obligate predators of termites (Hölldobler & Wilson 1990). In addition, Kenne et al. (2000) observed that *Myrmicaria opaciventris* can quickly subdued *Macrotermes bellicosus* soldier with its pretarsus and abdominal thorn, thereby attacking the workers. Nascimento (2001) reported that the *Pheidole pallidula* preyed on *Reticulitermes lucifugus*, which play an important role in suppressing the establishment of termite colonies. *Pachycondyla analis*, living in the dry forests of the Tanzanian coast and feeding on termites, can attack the termite nest (Bayliss & Fielding 2002). Ke et al. (2008) found that *Diacamma rugosum*, *Harpegnathos venator*, *Pachycondyla astuta* and *Polyrhachis* dives had strong agonistic behavior and attacking capabilities to *C. formosanus*, and also observed the ant nest adjacent to the *O. formosanus* nest and the ant predation behavior to termite in the wild. The defensive chemicals of ants how to affect termite is not well understood, let alone the utilization of those chemicals in termite control. Therefore, the aim of present work was to study the contact and fumigation toxicity of formic acid to *R. chinensis* in the laboratory.

Methods

Termite

The termite samples of *R. chinensis* colonies were collected from Huazhong Agriculture University, Wuhan, China. Colonies has been reared on wood pieces in a glass container (70 cm × 40 cm × 30 cm) in dark at 26 ± 1ºC and 80 ± 5% relative humidity for more than six months.

Contact toxicity

Contact toxicity of formic acid (98%, Sinopharm chemical Reagent Co., Ltd. China) to *R. chinensis* workers, alates (male and female) and soldiers was determined. For the ease of handling and obtaining uniform body weight, large workers were selected in the bioassay. Acetone was used as solvent, and the solution was applied with a 1.0 µl capillary tube. For workers, alates (male and female) and soldiers, doses of 100, 150, 200, 250, 300 and 350 µg adult^{-1} were applied. Controls were treated with acetone. Twenty adults of *R. chinensis* workers, alates (male and female) and soldiers were used for each concentration and control, and the experiment was replicated 3 times. Four colonies were used for workers. For alates (male and female) and soldiers, only one colony was tested. The contact toxicity of bifenthrin (98%, Huangma Agrochemicals Co., Ltd, Jiangsu, China) to *R. chinensis* workers was also estimated using 2 colonies. Doses of 3.125, 6.25, 12.5, 25.0 and 50.0 ng adult^{-1} were used. Bifenthrin is the most widely used commercial termiticide as positive control. Each dose was replicated 3 times, and each replicate consisted of 20 workers. Both treated and control insects were then transferred to glass Petri dishes, and kept under the same environmental conditions described for the rearing. Mortality percentages were recorded after treatment for 24 h and LD_{50} values were calculated according to Finney (1971).

Fumigation toxicity

To determine the fumigant toxicity of formic acid and the median effective time to cause mortality in 50 % of the workers from four different colonies (LT_{50} values), filter papers (Whatman No 1, cut into 2 cm diameter pieces) were impregnated with an appropriate concentration of 1.25, 2.5, 5.0, 10.0 and 20.0 µg ml^{-1}, respectively. The impregnated filter paper was then attached to the undersurface of the 1000 ml glass jar's (10 cm in diameter × 12.5 cm in height) screw cap, respectively. The cap was tightly screwed onto the jar, which contained 20 termites. In addition, workers from two other colonies were tested only at 2.5 µg ml^{-1}. Alates (male and female) and soldiers were also tested at 2.5 µg ml^{-1}. Two colonies were used for alates (male and female) and soldiers. Each concentration and control was replicated three times. Mortality was counted every minute after the formic acid had been delivered into the tube until all termites were dead. When no leg or antennal movements were observed, insects were considered dead.

Another experiment was designed in order to determine the 50% lethal concentration. For the mortality bioassay, 20 workers, 20 alates (male and female) or 20 soldiers were placed in the bottle. The number of dead termites was counted after the formic acid had been delivered into the bottle for 24 h. Six concentrations were tested, including 0.20, 0.40, 0.60, 0.80, 1.0 and 1.2 µg ml^{-1} for workers, alates (male and female) and soldiers, respectively. Three colonies were used for workers, and only one colony was used for alates (male and female) and soldiers. For each concentration × colony combination, there were three replicates. All bioassays were conducted at 26 ± 1ºC and 80 ± 5% relative humidity. The fumigation toxicity of bifenthrin (Huangma Agrochemicals

Co., Ltd, Jiangsu, China) on workers was also measured. Six concentrations were tested, including 0.125, 0.25, 0.625, 1.25 and 2.5 ng ml^{-1}. Two colonies were used, and there were three replicates for each colony.

Data analysis

Polo Plus v.1.0 (LeOra Software, Petaluma, CA) was used to estimate LD_{50}, KT_{50} and LC_{50} with 95% confidence intervals (CIs). The relative toxicity ratio with their upper and lower 95% confidence limits was used to evaluate the significance of the difference between LD_{50}, KT_{50} and LC_{50} values. The significance was set at the P = 0.05 probability level. If the 95% confidence interval of the ratio between two LD_{50}, KT_{50} or LC_{50} values included 1, these were not considered to be significantly different (Robertson et al. 2007).

Results

Toxicity of formic acid against *R. chinensis* was shown in Table 1. The LD_{50} values of formic acid were ranging from 267.86 to 287.68 µg adult^{-1} for workers, which were larger than those of bifenthrin with LD_{50} values ranging from 7.16 to 10.39 ng adult^{-1}, and no significant difference was also found in LD_{50} values of formic acid for workers between colony A and the other three colonies. Alates and soldiers were more sensitive to formic acid than workers. The LD_{50} values for alates (male and female) and soldiers were at 279.09 and 223.08 µg adult^{-1}, respectively.

Table 1- LD_{50} values of formic acid by contact against workers, alates and soldiers of *R. chinensis*.

Chemical	Colony	Caste [a]	Slope (±SE)	LD_{50}	95% CI
Formic Acid	A	W	2.36(±0.31)	287.68 (µg adult^{-1})	250.02-347.80
	B	W	2.09(±0.29)	286.24 (µg adult^{-1})	245.04-322.94
		A	2.91(±0.35)	279.09 (µg adult^{-1})	248.91-250.48
	C	W	2.54(±0.32)	273.77 (µg adult^{-1})	241.01-322.79
	D	W	2.21(±0.29)	267.86 (µg adult^{-1})	232.15-322.98
	E	S	2.93(±0.31)	223.08 (µg adult^{-1})	200.83-250.48
Bifenthrin [b]	E	W	2.52(±0.26)	7.16 (ng adult^{-1})	5.99-8.41
	F	W	2.46(±0.24)	10.39 (ng adult^{-1})	8.82-12.20

[a] W: works; A: alates (male and female); S: soldiers.
[b] Positive control.

As can be seen from Table 2, the LC_{50} values ranged from 0.84 to 1.08 µg ml^{-1} for workers, 1.19 µg ml^{-1} for alates (male and female) and 0.57 µg ml^{-1} for soldiers after treatment for 24 h, respectively. The LC_{50} values of a well-known commercial pesticide used as a positive control in this study, bifenthrin, were 0.40 and 0.42 ng ml^{-1}, respectively (Table 2). At a concentration of 2.50 µg ml^{-1}, the KT_{50} value of formic acid ranged from 25.38 to 34.75 min for workers, from 42.21 to 45.62 min for alates (male and female), from 32.18 to 36.37 min for soldiers (Table 3). Meanwhile, the higher the concentration, the smaller the KT_{50} value was. Within A colony, the KT_{50} value of workers was always significantly smaller than that of alates (male and female), and soldiers.

Table 2- LC_{50} values of formic acid applied as fumigant for 24 h against workers, alates and soldiers of *R. chinensis*.

Chemical	Colony	Caste [a]	Slope (±SE)	LC_{50}	95% CI
Formic Acid	A	W	6.71(±0.76)	0.95 µg ml^{-1}	0.88-1.03
	C	W	4.56(±0.52)	0.84 µg ml^{-1}	0.77-0.93
	B	W	4.39(±0.59)	1.08 µg ml^{-1}	0.98-1.23
		A	4.72(±0.73)	1.19 µg ml^{-1}	1.07-1.38
		S	4.77(±0.54)	0.57 µg ml^{-1}	0.49-0.65
Bifenthrin [b]	C	W	3.06(±0.29)	0.40 ng ml^{-1}	0.32-0.50
	D	W	2.80(±0.26)	0.42 ng ml^{-1}	0.35-0.50

[a] W: works; A: alates (male and female); S: soldiers.
[b] Positive control.

Discussion

When applied topically, formic acid was significantly less toxic to subterranean termite than bifenthrin, but higher toxic to many other pest insects. The LC_{50} value of formic acid for rice weevil, *Sitophilus oryzae*, was 6.03-7.60 µg ml^{-1}, and for the mosquito, *Culex quinquefasciatus*, was 3.67 µg ml^{-1} (Welling & Paterson 1985). Formic acid displayed low toxicity against yellow fever mosquito, *Aedes aegypti*, at 6.00 µg ml^{-1} (Chaskopoulou 2007). As demonstrated recently by Chen et al. (2012), the LC_{50} value of formic acid was 0.26-0.70 µg ml^{-1} for red imported fire ants. This indicated that the toxicity of formic acid to subterranean termite, *R. chinensis*, was higher than that of the insects studied so far, but similar to red imported fire ants.

Table 3- KT_{50} values of formic acid applied as fumigant against workers of *R. chinensis*.

Colony ID	Caste [a]	Dosage (µg/ml)	Slope (±SE)	KT_{50} (min)	95% CI
A	W	1.25	4.32(±0.77)	91.67	82.27-109.12
	W	2.5	7.87(±0.75)	26.71	25.47-28.01
	W	5.0	9.06(±1.00)	16.79	15.80-17.82
	W	10.0	9.63(±1.43)	8.74	7.78-9.34
	W	20.0	5.10(±0.58)	5.14	3.87-5.48
B	W	1.25	2.32(±0.28)	107.45	94.26-123.01
	W	2.5	8.45(±0.81)	32.85	31.61-34.25
	W	5.0	9.47(±0.88)	19.70	18.97-20.49
	W	10.0	6.24(±0.64)	9.55	9.05-10.05
	W	20.0	7.15(±0.72)	4.74	4.42-5.03
	A	2.5	7.77(±1.06)	45.62	43.34-48.79
	S	2.5	4.19(±0.51)	36.37	33.21-41.01
C	W	1.25	9.84(±0.84)	84.12	81.25-86.94
	W	2.5	7.95(±0.63)	25.38	24.21-26.51
	W	5.0	11.32(±0.96)	19.63	19.05-20.20
	W	10.0	14.18(±1.37)	7.74	7.44-8.04
	W	20.0	15.62(±1.63)	5.25	5.08-5.42
D	W	1.25	14.05(±1.35)	79.53	76.53-82.67
	W	2.5	12.03(±1.13)	29.74	28.49-31.07
	W	5.0	6.02(±0.66)	17.90	16.54-19.72
	W	10.0	8.56(±0.79)	6.31	5.94-6.68
	W	20.0	5.72(±0.64)	3.79	3.01-4.54
E	W	2.5	12.94(±1.24)	34.75	33.52-36.02
	A	2.5	9.40(±1.47)	42.21	40.14-45.72
	S	2.5	8.30(±1.44)	32.18	30.30-35.30
F	W	2.5	6.95(±0.62)	28.25	26.44-29.90

[a] W: works; A: alates (male and female); S: soldiers.

The action mode of formic acid was to inhibit the activity of mitochondrial cytochrome c oxidase (Nicholls 1975, Petersen 1977). Recently, formic acid has been reported to have a significant excitatory effect on the nervous system of housefly larvae (Song & Scharf 2008a, b). Song & Scharf (2009) reported the formic acid have a significant excitatory effect on the nervous system of *Drosophila melanogaster*. It may explain why formic acid has such a low contact toxicity compared with fumigation.

Fumigation has been extensively applied as building treatment in termite management programs. Fumigants include methyl bromide, sulfuryl fluoride, dichloroethane and dibromoethane. However, compared to contact insecticides, fumigation has lower toxicity. Therefore, the high efficacy of the conventional synthetic contact insecticides may have slowed down the development of any alternatives.

Using formic acid directly as fumigant against subterranean termite may not be suitable for its own acidity and corrosiveness. However, formate ester is much less corrosive than formic acid and should be much easier to handle. Scharf et al. (2006) and Nguyen et al. (2007) also found the low molecular weight formate esters are volatile compounds with fumigant insecticidal activity. Similarly, Chaskopoulou et al. (2009) reported the volatile low molecular weight compounds against *Aedes aegypti* and *Culex quinquefasciatus*. Previous research reported some formate esters had neurological activity on *Drosophila melanogaster* Meig and *Musca domestica* L, owning to their hydrolyzed metabolite, formic acid (Song & Scharf 2008a, b). Previously, Haritos & Dojchinov (2003) reported some formate esters exert toxicity in the stored product beetle *Sitophilus oryzae* L. for its hydrolyzed metabolite, formic acid, which causes mitochondrial impacts. Therefore, formate esters may also be as good candidates for subterranean termite, particularly as fumigant in treatment. However, the prerequisite is that formic acid can be liberated from formate esters in termite bodies. This is definitely worth for further investigation.

The formic acid fumigation bioassay to termite was carried out in an enclosed environment for termite control, such as house, storage spaces and timber. In order to make fumigation effectively, the enclosed environment must be intact during the application. Simultaneously, other factors such as temperature, humidity, the concentration and time of formic acid applied all should be considered. These are the key of successful application of formic acid in the termite control. In addition to considering their potential fumigant effect, like other commercial fumigant, the more important concern of formic acid application is its toxicity to humans and the environment. The current Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) is 3 mg m^{-3} as the 8 h time-weighted average (TWA) concentration for DDVP, 9 mg m^{-3} for formic acid, 80 mg m^{-3} for methyl bromide, 250 mg m^{-3} for methyl formate and ethyl formate is 300 mg m^{-3} (Chen et al. 2012). Therefore, the effect of formate esters against termite is more worth to investigate, as it seems that formate esters may be more practical to use than formic acid.

Acknowledgments

This study was supported by the Fundamental Research Funds for the Central Universities (2010PY065).

References

Attygalle A. B., J. Meinwald & T. Eisner 1992. Defensive secretion of a carabid beetle, *Helluomorphoides clairvillei*. J. Chem. Ecol., 18: 489-498.

Attygalle, A. B., S. R. Smedley, J. Meinwald & T. Eisner 1993. Defensive secretion of two notodontid caterpillars (*Schizura unicornis*, *S. badia*). J. Chem. Ecol., 19: 2089-2104.

Bayliss, J. & A. Fielding 2002. Termitophagous foraging by *Pachycondyla analis* (Formicidae: Ponerinae) in a Tanzanian coastal dry forest. Sociobiology, 39: 103-122.

Calderone, N. W. 2010. Evaluation of Mite-Away-II for fall control of *Varroa destructor* (Acari: Varroidae) in colonies of the honey bee *Apis mellifera* (Hymenoptera: Apidae) in the northeastern USA. Exp. Appl. Acarol. 50: 123-132.

Chaskopoulou, A. 2007. Testing vapor toxicity of formate, acetate, and heterocyclic compounds to *Aedes aegypti* and *Musca domestica*. MS Thesis, University of Florida, Gainesville, FL.

Chaskopoulou, A. S. Nguyen, R. M. Pereira, M. E. Scharf & P. G. Koehler 2009. Efficacy of 31 volatile low molecular weight compounds against *Aedes aegypti* and *Culex quinquefasciatus*. J. Med. Entomol., 46: 328-334.

Chang, S. T. & S. S. Cheng 2002. Antitermitic activity of leaf essential oils and components from *Cinnamomum osmophleum*. J. Agr. Food Chem., 50: 1389-1392.

Chen, J., T. Rashid & G. L. Feng 2012. Toxicity of formic acid to red imported fire ants, *Solenopsis invicta* Buren. Pest Manag. Sci. 68: 1393-1399.

Cheng, S. S., C. L. Wu, H. T. Chang, Y. T. Kao & S. T. Chang 2004. Antitermitic and antifungal activities of essential oil of *Calocedrus formosana* leaf and its composition. J. Chem. Ecol., 30: 1957-1967.

Chopra, R. N. & I. C. Chopra 2006. Indigenous Drugs of India. Bimal Kumar Dhur of Academic publishers, India.

Nascimento, F. S. 2001. Behavioral responses of Mediterranean termite *Reticulitermes lucifugus* (Rossi) (Isoptera: Rhinotermitidae) under presence effects of ant *Pheidole pallidula* (Nyl.) (Hymenoptera: Formicidae). Rev. Bras. Zooc., 3: 195-201.

Finney, D. J. 1971. Probit Analysis, 3rd edition. Cambridge University Press, Cambridge, UK.

Giovenazzo, P. & P. Dubreuil 2011. Evaluation of spring organic treatments against *Varroa destructor* (Acari: Varroidae) in honey bee *Apis mellifera* (Hymenoptera: Apidae) colonies in eastern Canada. Exp. Appl. Acarol., 55: 65-76.

Haritos, V. S. & G. Dojchinov 2003. Cytochrome c oxidase inhibition in the rice weevil *Sitophilus oryzae* by formate, the toxic metabolite of alkyl formates. Comp. Biochem. Physiol. C ,136: 135-143.

Hölldobler, B. & E. O. Wilson 1990 The Ants. Cambridge, Mass. Harvard University Press, 559-569.

Hoppe, H., W. Ritter & E. W. C. Stephen 1989. The control of parasitic bee mites: *Varroa jacobsoni*, *Acarapis woodi*, and *Tropilaelaps clareae* with formic acid. Am. Bee J., 129: 739-742.

Hutchens, A. R. 1992. A Handbook of Native American Herbs. Shambhala Publications, Massachusetts.

Ke, Y. L. T. Y. Zhuang, C. X. Wang, S. Zhao & W. J. Tian 2008. Agonistic behavior of six ant species to *Coptotermes formosanus* (Isoptera: Rhinotermitidae) in laboratory assays. Sociobiology, 51: 199-206.

Kenne, M., A. Dejean, R. Fénéron & J. L. Durand 2000. Changes in worker polymorphism in *Myrmicaria opaciventris* Emery (Formicidae: Myrmicinae). Insect. Soc., 47: 50-55.

Maistrello, L., G. Henderson & R. A. Laine 2001. Effects of nootkatone and a borate compound on formosan subterranean termite (Isoptera: Rhinotermitidae) and its symbiont protozoa. J. Entomol. Sci., 36: 229-236.

Meepagala, K. M., W. Osbrink, C. Burandt, A. Laxb & S. O. Dukea 2011. Natural-product-based chromenes as a novel class of potential termiticides. Pest Manag. Sci., 67: 1446-1450.

Nakashima, Y., & K. Shimizu 1972. Antitermitic activity of *Thujopsis dolabrata* var Hondai. III. Components with a termiticidal activity. Miyazaki Daigaku Nogakubu Kenkyu Hokoku, 19: 251-259.

Nelson, D., P. Mills, P. Sporns, S. Ooraikul & D. Mole 1994. Formic acid application methods for the control of honey bee tracheal mites. Bee Sci., 3: 128-134.

Nicholls, P. 1975. Formate as an inhibitor of cytochrome c oxidase. Bioch. Biophys. Res. Commun., 67: 610-616.

Nguyen, S. N., C. Song & M. E. Scharf 2007. Toxicity, synergism, and neurological effects of novel volatile insecticides in insecticide susceptible and resistant *Drosophila* strains. J. Econ. Entomol., 100: 534-544.

Potter, M. F. 1997. Termites, in Handbook of Pest Control, 8th edition, ed. by Hedges SA. Franzak & Foster, Cleveland, OH, pp. 233-333.

Petersen, L. C. 1977. The effect of inhibitors on the oxygen kinetics of cytochrome c oxidase. Bioch. Biophys. Acta, 460: 299-307.

Rahmatullah, M., R. Jahan, M. S. Hossan, S. Seraj, M. M. Rahman, A. R. Chowdhury, Z. U. M. E. U. Miajee, D. Nasrin, Z. Khatun, F. I. Jahan & M. A. Khatun 2010. A Comparative Analysis of Medicinal Plants used by Several Tribes of Chittagong Hill Tracts Region, Bangladesh to Treat Helminthic Infections. Adv. Nat. Appl. Sci., 4: 105-111.

Robertson, J. L., R. M. Russell, H. K. Preisler & N. E. Savin 2007. Bioassays with Arthropods, 2nd edition. CRC Press, Boca Raton, FL.

Rossini, C., A. B. Attygalle, A. Gonzalez, S. R. Smedley, M. Eisner, J. Meinwald & T. Eisner 1997. Defensive production of formic acid (80 percent) by a carabid beetle (*Galerita lecontei*). Proc. Nat. Acad. Sci. USA, 94: 6792-6797.

Scharf, M. E., S. N. Nguyen & C. Song 2006. Evaluation of volatile low molecular weight insecticides using *Drosophila melanogaster* as a model. Pest Manag. Sci., 62: 655-633.

Sharma, O. P., R. Garg & G. S. Dogra 1983. Efficacy of formic acid against *Acarapis woodi* (Rennie). Indian Bee J., 45: 1-2.

Song, C. & M. E. Scharf 2008a. Formic acid: a neurologically-active, hydrolyzed metabolite of insecticidal formate esters. Pest. Biochem. Physiol., 92: 77-82.

Song, C. & M. E. Scharf 2008b. Neurological disruption by low molecular weight compounds from the heterobicyclic and formate ester classes. Pest. Biochem. Physiol., 92: 92-100.

Song, C. & M. E. Scharf 2009. Mitochondrial impacts of insecticidal formate esters in insecticide-resistant and insecticide-susceptible *Drosophila melanogaster*. Pest Manag. Sci., 65: 697-703.

Su, N.Y. & R. H. Scheffrahn 1998. A review of subterranean termite control practices and prospects for integrated pest management programmes. Integr. Pest Manag. Rev., 3: 1-13.

Underwood, R. M. & R. W. Currie 2004. Indoor winter fumigation of *Apis mellifera* (Hymenoptera: Apidae) colonies with *Varroa destructor* (Acari: Varroidae) with formic acid is a potential control alternative in northern climates. J. Econ. Entomol., 97: 177-186.

Underwood, R. M. & R. W. Currie 2005. Effect of concentration and exposure time on treatment efficacy against *Varroa* mites (Acari: Varroidae) during indoor winter fumigation of honey bees (Hymenoptera: Apidae) with formic acid. J. Econ. Entomol., 98: 1802-1809.

Underwood, R. M. & R. W. Currie 2007. Effects of release pattern and room ventilation on survival of varroa mites and queens during indoor winter fumigation of honey bee colonies with formic acid. Can. Entomol., 139: 881-893.

UNEP/FAO/Global IPM Facility Expert Group on Termite Biology and Management, 2000. Finding alternatives to persistent organic pollutants (POPs) for termite management, online at www.chem.unep.ch/pops/termites/termite_ch4.htm.

vanEngelsdorp, D., R. M. Underwood & D. L. Cox-Foster 2008. Short-term fumigation of honey bee (Hymenoptera: Apidae) colonies with formic and acetic acids for the control of *Varroa destructor* (Acari: Varroidae). J. Econ. Entomol., 101: 256-264.

Verma, M., S. Sharma & R. Prasad 2009. Biological alternatives for termite control: A review. Int. Biodeter. Biodegr., 63: 959-972.

Weatherston J., J. E. Percy, L. M. MacDonald & J. A. MacDonald 1979 Morphology of the prothoracic defensive gland of *Schizura concinna* (J.E. Smith) (Lepidoptera: Notodontidae) and the nature of its secretion. J. Chem. Ecol., 5:165-177

Wei, J. Q., J. C. Mo, X. J. Wang & W. G. Mao 2007. Biology and ecology of *Reticulitermes chinensis* Snyder (Isoptera: Rhinotermitidae) in China. Sociobiology, 50: 553-559.

Will K. W., A. S. Gill, H. Lee & A. B. Attygalle 2010. Quantification and evidence for mechanically metered release of pygidial secretions in formic acid producing carabid beetles. J. Insect Sci., 10: 1-17.

Welling, W. & G. D. Paterson 1985. Toxicodynamics of insecticides, in Comprehensive Insect Physiology, Biochemistry and Pharmacology, Vol. 12, ed. by Kerkut GA and Gilbert LI. Pergamon, Oxford, UK, pp. 603-646.

Wilson, W.T., J. R. Baxter, A. M. Collins, R. L. Cox & T. D. Cardoso 1993. Formic acid fumigation for control of tracheal mites in honey bee colonies. Bee Sci., 3: 26-32.

Yoshida, S., Y. Morita, K. Narita & T. Okabe 1998. Termiticidal efficacy of neutral oil obtained from *Aomori hiba*. Tennen Yuki Kagobutsu Toronkai Koen Yoshishu, 40: 311-315.