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Research Article

Deltamethrin Resistance in Field Populations of *Rhyzopertha dominica* (Fabricius) (Coleoptera: Bostrichidae) Collected from Paddy Rice Warehouses in Taiwan

Wen-Bin Feng[1], Chi-Yang Lee[1], and Me-Chi Yao[2,*]

Abstract

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The lesser grain borer, *Rhyzopertha dominica* (Fabricius) is one of the most common stored product pests found in the paddy rice warehouses in Taiwan. Both larvae and adults can bite through the husk of paddy rice, causing serious losses. Currently, 0.055% dustable powder of deltamethrin is the only insecticide applied in the paddy rice warehouses to control the lesser grain borer in Taiwan. Deltamethrin has been recommended to control the stored product pests for 21 years since 2002. The long-term use of insecticides may lead to the development of insect resistance. In this study, we collected 21 *R. dominica* populations from paddy rice warehouses and obtained the deltamethrin resistance ratio of *R. dominica* with the rice-mixing method. The highest resistance ratios to deltamethrin were found in Wufeng, Hemei, Lukang, Minxiong, Liujiao, Houbi, Wandan, Dongshan, Yilan and Sanxing with the resistance ratios exceeding 117.65-fold. Results showed that *R. dominica* populations have developed high resistance to deltamethrin after a decade-long use of deltamethrin in Taiwan. To solve effectively control the lesser grain borer, it is necessary to find the alternative insecticides for controlling the stored product pests in paddy rice warehouses in Taiwan.

Key words: Paddy rice warehouse, *Rhyzopertha dominica*, Deltamethrin, Lethal concentration 50, Resistance ratio.

INTRODUCTION

The lesser grain borer, *Rhyzopertha dominica* (Fabricius) (Coleoptera: Bostrichidae), one of the primary stored product pests, mainly damaging corn, rice, wheat, and other cereal-stored products. It is widely distributed worldwide, including in the United States, Europe, India, China, and Australia (Edde 2012), and it is the most serious pest in paddy rice warehouses in Taiwan (Yao *et al*. 2022). Adults lay eggs on the surface of paddy rice, and both larvae and adults can bite through the paddy rice husk to invade the interior of the rice, causing damage. Its damage often produces rice powder, which could cause the outbreak of secondary pests such as the rusty grain beetle (*Cryptolestes ferrugineus* Stephens), the saw-toothed grain beetle (*Oryzaephilus surinamensis* (Linnaeus)), and the foreign grain beetle (*Ahasverus advena* (Waltl)). The lesser grain borer often leads to huge losses of rice and downgrades food safety in Taiwan.

To control damages caused by *R. dominica* during paddy rice storage, 0.055% dustable

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* Corresponding author, e-mail: yaomc@tari.gov.tw
1 Assistant Research Fellows, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.
2 Associate Research Fellow, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.

powder (DP) of deltamethrin was mixed evenly with paddy rice at a ratio of 1 : 750 in Taiwan, called the rice-mixing method. The Agriculture and Food Agency purchases a certain amount of deltamethrin commodities and delivers them to the managers of paddy rice warehouses across Taiwan every year. Using 0.055% deltamethrin DP had been recommended for controlling the lesser grain borer since 2002 (Yao & Lo 2000). The long-term use of insecticides with a single mechanism of action increased the stored product pests' chances of developing insecticide resistance. In recent years, many managers of paddy rice warehouses have frequently reported that deltamethrin is ineffective in controlling stored product pests such as the lesser grain borer and the Angoumois grain moth (*Sitotroga cerealella* (Olivier)). Additionally, some managers of warehouses would apply deltamethrin DP to the surfaces of 60-kg storage bags or above ton storage bags rather than mixing it with paddy rice. Since deltamethrin is a contact-type insecticide, the control effect of applying it to the storage bag surface could be ineffective. These incorrect application methods of deltamethrin fail to achieve the expected control effectiveness, increase unnecessary costs, and raise the risk of resistance development in stored product pests to deltamethrin. *R. dominica* resistance to deltamethrin has been reported in many countries, including Taiwan (Chen & Chen 2013), Australia (Daglish & Nayak 2018), Brazil (Lorini & Galley 1999), and India (Ramesh Babu *et al*. 2017a, 2017b). Chen & Chen (2013) first revealed the presence of deltamethrin resistance in *R. dominica* with the highest resistance ratio (RR) of 63.8 in Nantou, Taiwan. After ten more years of using deltamethrin, the deltamethrin resistance in *R. dominica* populations may have increased even more.

In this study, *R. dominica* adults were collected from paddy rice warehouses across Taiwan, and the LC_{50} of deltamethrin of each strain was determined to understand the development of deltamethrin resistance in *R. dominica* populations.

MATERIALS AND METHODS

Sampling site and insect rearing

Adults of *R. dominica* were collected from 21 paddy rice warehouses in northern, central, southern, and eastern Taiwan (Fig. 1) between September 2022 and October 2023.

The collected adult beetles were reared in plastic containers (radius: 12 cm; height: 5 cm) with oatmeal as their food source. Additionally, a strain that had not been exposed to insecticides for at least 10 years in the laboratory was used as the most susceptible population in this study. All strains were maintained in the Laboratory of Integrated Pest Management, Applied Zoology Division, Taiwan Agricultural Research Institute, in environmental chambers with a temperature set at 27 ± 1℃ and relative humidity at 70 ± 5%, and 24-h darkness.

Insecticide

A technical-grade deltamethrin (99.4%; Dr. Ehrenstorfer GmbH, Augsburg, Germany) was used to examine the deltamethrin resistance of *R. dominica* strains collected from each warehouse. The deltamethrin was diluted with acetone to the respective concentrations for insecticide resistance bioassays.

Insecticide resistance bioassays

To simulate the actual application of deltamethrin DP (the recommended formulation in Taiwan) in paddy rice warehouses, the rice-mixing method was employed in this study (Yao & Lo 2000). Erlenmeyer flasks (radius: 2.5 cm; height: 9 cm) were prepared with 0.1 g of talcum powder, into which 1 mL of each concentration of deltamethrin was dripped onto the bottom of the flask. The mixture of talcum powder and deltamethrin solution was air-dried at 27 ± 1℃ and 70 ± 5% relative humidity for 3 h. The 10 g paddy rice (cultivar: 'Tainan No. 11') grains were poured into the flask, and mixed with the deltamethrin-treated talcum powder using a Vortex mixer (Scientific Industries, Inc., New York, USA). Thirty unsexed

Fig. 1. Locations where *Rhyzopertha dominica* adults were collected from paddy rice warehouses in Taiwan. ● denotes *R. dominica* populations with a high degree of deltamethrin resistance.

F_2-F_3 *R. dominica* adults (2-to-3 weeks old) were added into the flask to initiate the experiment. Each strain was treated with five to seven concentrations of deltamethrin, ranging from 0.01 mg mL^{-1} to 10 mg mL^{-1}, and the control was treated with acetone only. Each concentration was replicated three times. All treatments were maintained at 27 ± 1℃, 70 ± 5% relative humidity, and a 12 : 12 h photoperiod for 24 h. Mortality was observed after 24 h, and individuals with no response to touching were considered dead.

Statistical analysis

The concentration causing 50% *R. dominica* population mortality (LC_{50}), the 95% fiducial limits (FL) of LC_{50}, and the chi-squared test were obtained using Probit analysis in the SPSS program (Version 23). The resistance ratio of each strain was generated from the LC_{50} of each strain divided by the LC_{50} of the laboratory strain in this study. If the mortality was less than 50% at 10 mg mL^{-1} deltamethrin, the LC_{50} was stated as > 10 mg mL^{-1} while the resistance ratio was shown as > 117.65-fold.

The degrees of resistance ratio were classified as follows: low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160, and extremely high for RR ≥ 160 (Hayashi 1983).

RESULTS

Among the 22 populations of *R. dominica* (Table 1), the Lab strain required the lowest concentration of 0.085 mg mL^{-1} to cause 50% population mortality. The highest deltamethrin resistance was found in several strains collected from Wufeng, Hemei, Lukang, Minxiong, Liujiao, Houbi, Wandan, Dongshan, Yilan, and Sanxing, all with the LC_{50} greater than 10 mg mL^{-1}. Five strains were determined from northern Taiwan, among which *R. dominica* populations of Tongluo were classified as moderate resistance to deltamethrin, with a resistance ratio of 10.31-fold. The strain from Yuanli was classified as high deltamethrin resistance, with a resistance ratio of 48.53-fold compared with

Table 1. Susceptibility, resistance ratio (RR), and degree of resistance of *Rhyzopertha dominica* populations to deltamethrin in paddy rice warehouses in Taiwan.

Strain	N[z]	LC_{50} (95% FL[y]) mg mL^{-1}	Slope	χ^2	*df*	RR[x]	Degree of resistance[w]
Laboratory	450	0.085 (0.044–0.139)	1.56	38.66	13	1.00	Low
Northern							
Yangmei	450	0.542 (0.316–1.318)	0.63	22.52	13	6.38	Low
Houlong	450	0.209 (0.112–0.354)	0.52	14.04	13	2.46	Low
Tongxiao	540	0.646 (0.391–1.188)	0.53	15.66	16	7.60	Low
Tongluo	540	0.876 (0.467–2.027)	0.44	23.83	16	10.31	Moderate
Yuanli	630	4.125 (3.253–5.467)	1.47	12.87	19	48.53	High
Central							
Houli	540	1.291 (0.764–2.896)	0.84	10.75	16	15.19	Moderate
Wufeng	450	> 10.00	-	-	-	> 117.65	High
Shengang	450	0.826 (0.526–1.742)	0.88	10.59	13	9.72	Low
Hemei	450	> 10.00	-	-	-	> 117.65	High
Lukang	450	> 10.00	-	-	-	> 117.65	High
Southern							
Minxiong	450	> 10.00	-	-	-	> 117.65	High
Liujiao	450	> 10.00	-	-	-	> 117.65	High
Houbi	450	> 10.00	-	-	-	> 117.65	High
Wandan	450	> 10.00	-	-	-	> 117.65	High
Eastern							
Toucheng	630	0.213 (0.154–0.313)	0.95	22.01	19	2.51	Low
Jiaoxi	540	1.328 (0.654–5.171)	0.86	22.67	16	15.63	Moderate
Dongshan	450	> 10.00	-	-	-	> 117.65	High
Yilan	450	> 10.00	-	-	-	> 117.65	High
Sanxing	450	> 10.00	-	-	-	> 117.65	High
Changbin	450	0.108 (0.083–0.141)	1.17	21.31	13	1.27	Low
Taitung	540	1.122 (0.642–2.340)	0.50	10.78	16	13.20	Moderate

[z] Number of *R. dominica* adults tested.
[y] Estimated lethal concentration values with fiducial limits (FL).
[x] Resistance ratio = LC_{50} of each strain divided by LC_{50} of Lab-strain.
[w] Degree of resistance ratio was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160, and extremely high for RR ≥ 160.

the Lab strain. Five strains were identified in central Taiwan, *R. dominica* populations were classified as moderate resistance to deltamethrin with an LC_{50} of 1.291 mg mL^{-1} in Houli. While strains from Wufeng, Hemei, and Lukang displayed high deltamethrin resistance, with the resistance ratio of greater than 117.65-fold compared with the Lab strain. In southern Taiwan, all strains showed high deltamethrin resistance, with resistance ratios exceeding 117.65-fold compared with the Lab strain. Among 7 strains of *R. dominica* identified in eastern Taiwan, populations from Jiaoxi and Taitung were classified as moderate deltamethrin resistance with the LC_{50} ranging from 1.122 to 1.328 mg mL^{-1}. The *R. dominica* populations were classified as high deltamethrin resistance, with resistance ratios more than 10 mg mL^{-1} in Dongshan, Yilan and Sanxing. In contrast, strains from Toucheng and Changbin were classified as low resistance to deltamethrin, with a resistance ratio of 2.51 and 1.27, respectively.

Overall, 19.0% of the collected strains were moderate resistance to deltamethrin, while 52.4% of collected strains showed high deltamethrin resistance.

DISCUSSION

In this study, *R. dominica* populations from paddy rice warehouses have developed a certain deltamethrin resistance in Taiwan. Of 21 strains tested, 52.4% showed high resistance to deltamethrin, with the highest resistance ratio exceeding 117.65-fold, which is higher than reported by Chen & Chen (2013) at 63.8-fold in 25.0% of populations. It meant that the deltamethrin resistance of *R. dominica* became more serious after 11 years of deltamethrin application. Among these 21 strains, *R. dominica* populations in southern Taiwan showed a high frequency of deltamethrin resistance. This could be attributed to higher temperatures in the south of region compared to other regions, which led to higher reproductive rates of *R. dominica* populations and accelerated the development of insecticide resistance (Edde 2012).

Currently, 3 possible reasons are speculated for the occurrence of deltamethrin resistance in *R. dominica* populations from paddy rice warehouses. First is the long-term use of insecticides with a single mode of action. Between 1992 and 1995, it was successively discovered that *Sitophilus zeamais* Motschulsky and *Corcyra cephalonica* (Stainton) are resistant to the organophosphate phoxim (Kao & Tzeng 1992; Yao & Lo 1994, 1995). Subsequently, experiments conducted in 2000 confirmed that deltamethrin mixed with paddy rice could effectively control *R. dominica* and *S. cerealella* lasting for over a year (Yao & Lo 2000). Therefore, the pyrethroid deltamethrin has been recommended to replace the organophosphate phoxim for controlling stored product pests in paddy rice warehouses since 2002. Even though the organophosphate malathion is another recommended insecticide with the paddy rice-mixing method to control stored product pests, it was discovered that *S. cerealella* collected from Pingtung had developed resistance to malathion, with a resistance ratio of 111-fold (Kao & Tzeng 1992). This finding prompted the Agriculture and Food Agency to purchase only deltamethrin for warehouse managers in Taiwan for 21 years. Consequently, it may lead to the increase of selection pressure from a single insecticide, resulting in the development of *R. dominica* with high resistance to deltamethrin. Second is the incorrect application of deltamethrin DP. Since deltamethrin is a contact-type insecticide, it cannot contact the stored product pests of paddy rice if it is applied only to the exterior of storage bags. This not only fails to control stored product pests effectively, but also increases costs and risk of generating high resistance of stored product pests to deltamethrin. Moreover, insufficient exposure of insects to the insecticide may lead to insecticide-induced hormesis, which increases insect reproduction by enhancing the mating behavior or fecundity at low doses of insecticide treatments (Qu *et al*. 2015; Tuelher *et al*. 2017; Feng *et al*. 2019; Malbert-Colas *et al*. 2020). Exposure of pyrethroid-resistant *S. zeamais* to 0.05 ppm deltamethrin led to a relatively high net reproductive rate (R_0) and intrinsic rate of increase (r_m), whereas maize weevils treated with 0.5 to 5 ppm of deltamethrin showed relatively low offspring body mass, net reproductive rate (R_0) and intrinsic rate of increase (r_m) (Guedes *et al*. 2010). Outbreaks of stored product pests may occur rapidly after incorrect deltamethrin application due to insecticide-induced hormesis. Third is the transportation of paddy rice between warehouses. Since there is insufficient space for warehouses and processing machinery such as paddy dryers and rice milling machines, some paddy rice may be transferred to other warehouses for storage or processing. This transportation of paddy rice might allow the high deltamethrin-resistant *R. dominica* to spread to other warehouses and lead to the occurrence of deltamethrin resistance for *R. dominica* in the paddy rice warehouses where no insecticides were applied. Therefore, it is necessary to carefully assess the presence of high insecticide-resistant *R. dominica* populations in the original storage location before transporting paddy rice around.

To address the development of deltamethrin resistance in *R. dominica* populations, solutions could include: (1) reducing the frequency of insecticide applications and (2) employing alternative insecticides with different modes of action. Preventing the development of insecticide resistance in pests is more crucial than controlling pests that have already developed high resistance to insecticides. Practicing good sanitation for processing machines such as paddy dryers and rice milling machines and applying non-chemical control materials such as ventilation fans, light traps, pheromones, and natural enemies are the ideal strategies to delay the development of insecticide resistance in insects. (Boyer *et al*. 2012; Edde 2012; Yao *et al*. 2022). Additionally, using alternative insecticides may serve as an effective method to combat the high deltamethrin-resistant lesser grain borer. Currently, insecticides that can potentially control *R. dominica* are categorized into three groups with seven different modes of action (Table 2). The first category of insecticides that are currently registered for mixing with paddy rice in Taiwan includes organophosphate malathion. Malathion was initially recommended for mixing with paddy rice in 1971. However, malathion was replaced by phoxim after the occurrence of malathion resistance in stored product pests in 1979. High malathion-resistant *S. cerealella* was still identified 13 years after 1979 (Kao & Tzeng 1992). After 32 years without malathion application since 1992, the malathion resistance of stored product pests may have declined. The Agriculture and Food Agency could consider providing malathion to warehouse managers for controlling *R. dominica* if a decline of malathion resistance in stored product pests is confirmed, and the pesticide companies would supply it again. The second category of insecticides includes organophosphate phoxim and pyrethroid permethrin, which are recommended for disinfecting empty warehouses. Although this category of insecticides is not used for paddy rice-mixing, but they are registered for controlling the stored product pests in empty warehouses. Therefore, this category of insecticides could potentially be used in paddy rice-mixing, and the pesticides-registration process could be simpler than pesticides that have not been registered in Taiwan. The third category of insecticides is used internationally to control *R. dominica*, but it has not been registered for use in warehouses in Taiwan. This category of insecticides includes pyrethroid phenothrin, spinosyn spinosad, avermectin abamectin, juvenile hormone analogue methoprene, bacterium *Bacillus thuringiensis* subsp. *kurstaki*/*tenebrionis* and fungal agent *Beauveria bassiana* (Mummigatti *et al*. 1994; Beegle 1996; Lord 2005; Oppert *et al*. 2010; Boyer *et al*. 2012; Rumbos *et al*. 2014; Mohamed 2016; Akmal *et al*. 2017; Perišić *et al*. 2020). Spinosad was considered one of the insecticides that can effectively control the lesser grain borer (Fang *et al*. 2002; Chintzoglou *et al*. 2008; Daglish *et al*. 2008; Ramesh Babu *et al*. 2017a). Chen & Chen (2013) confirmed that spinosad was effective in controlling the high

Table 2. The current-registered insecticides that have the potential for controlling *Rhyzopertha dominica* in paddy rice warehouses.

Insecticides[z]	Registered status in warehouses in Taiwan[y]
1B Organophosphates	
Malathion	Recommended for paddy rice-mixing and empty warehouse disinfection
Phoxim	Recommended for empty warehouse disinfection
3A Pyrethroids	
Permethrin	Recommended for empty warehouse disinfection
Phenothrin	Not recommended in warehouses
5 Spinosyns	
Spinosad	Not recommended in warehouses
6 Avermectins & Milbemycins	
Abamectin	Not recommended in warehouses
7A Juvenile hormone analogues	
Methoprene	Not recommended in warehouses
11A *Bacillus thuringiensis*	
B. thuringiensis subsp. *kurstaki*	Not recommended in warehouses
B. thuringiensis subsp. *tenebrionis*	Not recommended in warehouses
UNF Fungal agents	
Beauveria bassiana	Not recommended in warehouses

[z] Insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The information on registered insecticides for warehouses was collected from the pesticide information service website (https://pesticide.aphia.gov.tw/information, visited on 2024/06/16) under the Animal and Plant Health Inspection Agency, Ministry of Agriculture, Taiwan.

deltamethrin-resistant *R. dominica* populations collected from Nantou as well as from the 15 strains in Taiwan. However, due to its higher cost than deltamethrin, spinosad was not used in paddy rice warehouses at that time. Methoprene, one of the insect growth regulators, is relatively non-toxic to humans, mammals, and fish. Methoprene does not directly kill insect adults but rather interferes with the development of immature stages, thereby reducing the offspring number. Globally, it is believed that alternating methoprene with deltamethrin or spinosad can effectively control *R. dominica* (Arthur 2004; Athanassiou *et al*. 2011; Arthur 2019). To diversify insecticide options used in paddy rice warehouses, selecting alternative insecticides requires further investigations in Taiwan. In addition to finding alternative insecticides, exploring the resistance mechanisms of *R. dominica* against deltamethrin will be a crucial focus for future research. Understanding these resistance mechanisms may assist in improving pest resistance management strategies in paddy rice warehouses.

Currently, most warehouse managers prefer to apply deltamethrin DP to the exterior of storage bags. This preference likely comes from concerns over the labor-intensive and time-consuming process of rice mixing method, as well as the potential respiratory health risks associated with dust. Therefore, we believe it is necessary to collaborate with agricultural machinery experts to incorporate the paddy rice-mixing method of insecticides into the standard operating procedures for the paddy rice drying process. By doing so, warehouse managers may be more willing to apply insecticide DP appropriately.

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臺灣稻穀倉庫中穀蠹 (鞘翅目：長蠹蟲科) 對第滅寧之感受性評估

馮文斌[1]　李啟陽[1]　姚美吉[2,*]

摘要

馮文斌、李啟陽、姚美吉。2025。臺灣稻穀倉庫中穀蠹 (鞘翅目：長蠹蟲科) 對第滅寧之感受性評估。台灣農業研究 74(1):1–10。

穀蠹 (*Rhyzopertha dominica* (Fabricius)) 為我國公糧稻穀倉庫中最常見的主要害蟲，其幼蟲與成蟲均能咬破稻穀的穎殼，直接侵入稻穀內部取食，造成嚴重危害。目前公糧稻穀儲藏期間主要使用 0.055% 第滅寧粉劑與稻穀均勻混拌來防治穀蠹。然而自 2002 年推薦使用第滅寧至今，長期使用單一作用機制的藥劑可能已導致積穀害蟲產生抗藥性。本研究從臺灣各地稻穀倉庫採集 21 個穀蠹族群，並透過稻穀混拌法取得穀蠹對第滅寧的抗藥性數據，結果顯示霧峰、鹿港、民雄、六腳、後壁、萬丹、冬山、宜蘭及三星地區的抗藥性最為嚴重，抗性比最高超過 117.65 倍，證實經過多年連續使用，確實已經導致穀蠹發展出第滅寧抗藥性。為解決因抗藥性引起的第滅寧殺蟲效果下降問題，未來將逐步篩選替代藥劑，以增加我國公糧稻穀倉庫混拌藥劑的種類，減少因抗藥性造成之積穀害蟲防治效果不彰。

關鍵詞：稻穀倉、穀蠹、第滅寧、半致死濃度、抗性比。

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[*] 通訊作者：yaomc@tari.gov.tw
[1] 農業部農業試驗所應用動物組助理研究員。臺灣 臺中市。
[2] 農業部農業試驗所應用動物組副研究員。臺灣 臺中市。