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Research Article

Susceptibility of Deltamethrin-Resistant *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) to Alternative Insecticides

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Abstract

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The lesser grain borer, *Rhyzopertha dominica* (Fabricius), is a major pest of stored paddy rice in Taiwan. Deltamethrin has been the primary insecticide recommended for rice-mixing applications in warehouses since 2002. However, its long-term use has led to widespread resistance in field populations, particularly in central and southern Taiwan. To identify potential alternative insecticides, this study evaluated the susceptibility of 20 field-collected *R. dominica* populations with varying levels of deltamethrin resistance to six insecticides representing four different modes of action: 1B organophosphates- malathion and phoxim; 3A pyrethroids- permethrin and phenothrin; 5 spinosyns- spinosad; and 6 avermectins & milbemycins- abamectin. Laboratory bioassays using the rice-mixing method revealed that most populations remained susceptible to malathion, phoxim, spinosad, and abamectin compared to the laboratory population. In contrast, all tested populations showed high resistance to phenothrin. Although some populations showed only moderate resistance to permethrin compared to the laboratory population, they demonstrated extremely high LC_{50} values exceeding 10,000 μg mL^{-1}, indicating limited field utility. These findings suggest that malathion, phoxim, spinosad, and abamectin show potential as alternative insecticides for managing deltamethrin-resistant *R. dominica* in paddy rice warehouses. Field trials are required to validate their efficacy, determine appropriate operational dosages under practical conditions to support future insecticide registration, as well as to establish a science-based insecticide rotation strategy in paddy rice warehouses in Taiwan.

Key words: *Rhyzopertha dominica*, Alternative insecticides, Lethal concentration 50%, Resistance ratio, Level of insecticide resistance.

INTRODUCTION

Rice (*Oryza sativa* Linnaeus) is the third most important staple crop worldwide, following wheat and corn, with an annual production of approximately 776.5 million tons, serving as a primary source of calories for billions of people (FAO 2024). In Taiwan, rice is generally cultivated twice a year across most regions. A portion of the harvested paddy rice is purchased by the government, dried, and stored in designated warehouses as emergency grain reserves, with a maximum storage period of up to three years. However, Taiwan's geographical location as a subtropical island, coupled with the influence of continental air currents, results in persistently high temperatures and humidity. Moreover, the widespread use of sealed, poorly

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ventilated paddy rice storage facilities creates conditions, highly conducive to the reproduction of stored-product pests. Consequently, paddy rice during storage is frequently infested by several stored-product pests, including *Sitophilus oryzae* (Linnaeus), *Rhyzopertha dominica* (Fabricius), *Cryptolestes ferrugineus* (Stephens), *Oryzaephilus surinamensis* (Linnaeus), and *Lophocateres pusillus* (Klug). These infestations cause substantial quantitative and qualitative losses in paddy rice, with *R. dominica* being the most destructive species (Yao *et al*. 2019, 2022).

R. dominica (Coleoptera: Bostrichidae), commonly known as the lesser grain borer, is a primary pest of cereal-stored products worldwide, particularly in tropical and subtropical regions. It often causes economic losses in maize, rice, wheat and other cereals during storage (Edde 2012). Both larvae and adults are capable of biting the husk of paddy rice and feeding on the endosperm within. This feeding activity results in the fragmentation of paddy rice into powder, which serves as a food source for secondary stored-product pests such as *C. ferrugineus*, *O. surinamensis*, and *Ahasverus advena* (Waltl), thereby exacerbating damage and increasing the risk of grain deterioration. Furthermore, the strong flight ability and phototactic behavior of *R. dominica* often disturb residents living near warehouses, especially between 16:00 and 18:00 (Yao *et al*. 2022), making it not only an economic pest but also a nuisance pest.

Current control methods for stored-product pests rely heavily on insecticide application, which is considered the most effective method for quickly reducing pest populations below the economic injury level (EIL) (Edde 2012). Organophosphates and pyrethroids were the primary insecticides used to control stored-product pests in stored cereals, with deltamethrin being one of the most commonly applied compounds. However, the long-term use of insecticides with a single mode of action may lead to the development of resistance, particularly in pests with short life cycles. Between 1995 and 2012, four species of stored-product pests- *R. dominica*, *S. granarius* (Linnaeus), *S. zeamais* (Motschulsky) and *Tribolium castaneum* (Herbst) were reported to have developed resistance to deltamethrin (Boyer *et al*. 2012). Subsequently, deltamethrin-resistant *R. dominica* populations have been progressively documented in various countries, including Australia (Daglish & Nayak 2018), Brazil (Lorini & Galley 1999), Colombia (Ortega *et al*. 2021), India (Ramesh Babu *et al*. 2017a) and Taiwan (Chen & Chen 2013; Feng *et al*. 2025). In Taiwan, deltamethrin has been the recommended insecticide for controlling stored-product pests in paddy rice warehouses since 2002 (Yao & Lo 2000). Resistance of *R. dominica* to deltamethrin in Taiwan was first reported by Chen & Chen (2013), with the Nantou population exhibiting a resistance ratio of 63.8-fold with an LC_{50} value of 1.276 mg kg^{-1}. After a 12-year interval, Feng *et al*. (2025) reported that 52.4% of the field-collected *R. dominica* populations exhibited high resistance to deltamethrin, with the highest resistance ratio exceeding 117.65-fold. Notably, the proportion of highly deltamethrin-resistant *R. dominica* populations was particularly high in central and southern Taiwan, reaching 60% and 100% respectively (Feng *et al*. 2025). These findings highlight the escalating severity of deltamethrin resistance in *R. dominica*, underscoring the urgent need for effective alternative insecticides to sustain effective pest control and minimize postharvest losses during paddy rice storage.

In this study, the susceptibility of 20 field-collected *R. dominica* populations to six insecticides with four different modes of action, previously described as potential alternative insecticides by Feng *et al*. (2025), was evaluated. The findings aim to provide a scientific reference for selecting alternative insecticides to replace deltamethrin for the control of *R. dominica* in paddy rice warehouses in Taiwan.

MATERIALS AND METHODS

Insect collection and rearing

One susceptible population of *R. dominica*, maintained in the laboratory for over 10 years without exposure to any insecticides, and 20 field populations were used in this study. Field populations were collected from paddy rice warehouses across Taiwan between September 2022 and October 2023. Detailed information on collection locations is provided in Feng *et al.* (2025).

All populations were reared in plastic containers (diameter: 12 cm, height: 5 cm) with oatmeal provided as their food source. Colonies were maintained in the Laboratory of Integrated Pest Management, Applied Zoology Division, Taiwan Agricultural Research Institute, under controlled environmental conditions of 27 ± 1℃ and 70 ± 5% relative humidity (RH), with continuous darkness.

Insecticides

Technical-grade insecticides were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany) and included the following active ingredients: 1B organophosphates- malathion (98.60%) and phoxim (97.26%); 3A pyrethroids- permethrin (98.10%) and phenothrin (94.50%); 5 spinosyns- spinosad (93.92%); and 6 avermectins & milbemycins- abamectin (95.69%). Each insecticide was diluted to the desired concentration with acetone and used in subsequent insecticide susceptibility bioassays.

Insecticide susceptibility bioassays

The rice-mixing method was employed to simulate the practical application of insecticide dustable powder, which is the recommended formulation for managing stored-product pests in paddy rice in Taiwan (Yao & Lo 2000). Erlenmeyer flasks (diameter: 5 cm, height: 9 cm) were prepared by first adding 0.1 g of talcum powder, followed by application of 1 mL of insecticide solution at the designated concentration onto the bottom of the flask. The mixture of talcum powder and insecticide solution was left to air-dry under controlled conditions (27 ± 1℃, 70 ± 5% RH) for 3 h to ensure complete evaporation of acetone. After drying, 10 g of paddy rice grains (cultivar: 'Tainan No. 11'; the predominant cultivar cultivated in Taiwan) were introduced into the Erlenmeyer flask and thoroughly mixed with the insecticide-treated talcum powder using a Vortex mixer (Scientific Industries, Inc., New York, NY, USA). Subsequently, thirty unsexed *R. dominica* (F_2–F_3 generation, 2–3 wk old) adults were placed into each flask to initiate the bioassay. Each population was exposed to five concentrations of each insecticide, while the control group was treated with acetone alone. Each concentration was tested in triplicate. All treatments were kept at 27 ± 1℃, 70 ± 5% RH, and a 12 : 12 h (L : D) photoperiod for 24 h. Mortality was evaluated after 24 h, and insects showing no response to touch were considered dead.

Data analysis

Mortality data were analyzed using Probit analysis in the SPSS software (Version 23). The lethal concentration required to cause 50% mortality (LC_{50}), along with its 95% fiducial limits (FL) and chi-squared (χ^2) values, were obtained for each population and insecticide. Resistance ratios (RR) of each population to each insecticide were calculated from the LC_{50} of each population divided by that of the laboratory population. If the mortality of the population was less than 50% at the highest tested insecticide concentration (10,000 μg mL^{-1}), the LC_{50} was recorded as > 10,000 μg mL^{-1}. Based on RR values, resistance levels were classified as follows: low (RR ≤ 10), moderate (10 < RR ≤ 40), high (40 < RR ≤ 160), and extremely high (RR > 160) (Hayashi 1983).

RESULTS

1B Organophosphates: malathion and phoxim

The LC_{50} and RR values of *R. dominica* in response to malathion are shown in Table 1. The Toucheng population was most susceptible to malathion, with an LC_{50} of 141 μg mL^{-1}. All tested populations were susceptible to malathion, displaying LC_{50} values between 141

Table 1. Susceptibility, resistance ratio (RR), and resistance level of *Rhyzopertha dominica* populations to malathion.

	Malathion (1B organophosphates[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	213 (164–287)	1.13	10.6 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	917 (629–1,410)	0.98	27.3 (13)	4.31	Low	6.38	Low
Tongxiao	450	505 (340–875)	1.22	23.5 (13)	2.37	Low	7.60	Low
Tongluo	450	1,368 (1,064–1,864)	1.42	14.0 (13)	6.42	Low	10.31	Moderate
Yuanli	450	523 (345–935)	0.82	15.7 (13)	2.46	Low	48.53	High
Central								
Houli	450	433 (306–680)	0.94	7.8 (13)	2.03	Low	15.19	Moderate
Wufeng	450	262 (203–347)	1.34	3.4 (13)	1.23	Low	> 117.65	High
Shengang	450	507 (399–681)	1.57	5.8 (13)	2.38	Low	9.72	Low
Hemei	450	992 (612–2,014)	0.82	17.6 (13)	4.66	Low	> 117.65	High
Lukang	450	225 (148–363)	1.11	20.8 (13)	1.06	Low	> 117.65	High
Southern								
Minxiong	450	204 (103–551)	0.76	33.5 (13)	0.96	Low	> 117.65	High
Liujiao	450	267 (167–505)	0.37	20.3 (13)	1.25	Low	> 117.65	High
Houbi	450	456 (277–873)	0.82	3.7 (13)	2.14	Low	> 117.65	High
Wandan	450	647 (517–857)	1.89	11.7 (13)	3.04	Low	> 117.65	High
Eastern								
Toucheng	450	141 (88–225)	0.73	10.0 (13)	0.66	Low	2.51	Low
Jiaoxi	450	146 (93–225)	0.76	15.0 (13)	0.69	Low	15.63	Moderate
Dongshan	450	869 (696–1,165)	1.96	6.2 (13)	4.08	Low	> 117.65	High
Yilan	450	1,948 (1,702–2,270)	1.14	39.3 (13)	9.15	Low	> 117.65	High
Sanxing	450	891 (620–1,564)	1.33	9.5 (13)	4.18	Low	> 117.65	High
Changbin	450	366 (176–1,204)	0.88	29.1 (13)	1.72	Low	1.27	Low
Taitung	450	729 (467–1,393)	0.76	21.7 (13)	3.42	Low	13.20	Moderate

[z] The insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al.* (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

and 1,948 μg mL^{-1} and RR values from 0.66- to 9.15-fold relative to the laboratory population. All tested populations with moderate to high resistance to deltamethrin remained susceptible to malathion compared with the laboratory population.

The LC_{50} and RR values of *R. dominica* for phoxim are listed in Table 2. The Toucheng and Yilan populations were the most susceptible to phoxim among the tested populations, with LC_{50} of 6 μg mL^{-1}. All tested populations exhibited susceptibility to phoxim, with LC_{50} values ranging from 6 to 100 μg mL^{-1} and RR values ranging from 0.27- to 4.55-fold compared with the laboratory population. All tested populations exhibiting moderate to high resistance to deltamethrin remained susceptible to phoxim, and those with low deltamethrin resistance were likewise generally susceptible when compared with the laboratory population.

3A pyrethroids: permethrin and phenothrin

The LC_{50} and RR values for *R. dominica* exposed to permethrin are detailed in Table 3. The Changbin population exhibited the highest susceptibility to permethrin among the tested populations, with an LC_{50} of 60 μg mL^{-1}. In contrast, the Wufeng, Hemei, Wandan, Jiaoxi, and Yilan populations showed moderate levels of resistance, each with LC_{50} values exceeding 10,000 μg mL^{-1} and RR values greater than 15.17-fold relative to the laboratory population. Most tested populations with high deltamethrin resistance were susceptible to permethrin when compared with the laboratory population. The Wufeng, Hemei, Wandan, Jiaoxi, and Yilan populations, all of which exhibited moderate to high deltamethrin resistance, consistently showed moderate resistance to permethrin.

The LC_{50} and RR values for *R. dominica* with phenothrin are shown in Table 4. The laboratory population exhibited the highest susceptibility to phenothrin, with an LC_{50} value of 130 μg mL^{-1}. However, all tested populations showed high resistance to phenothrin, regardless of their deltamethrin resistance level. All tested populations had LC_{50} values exceeding 10,000 μg mL^{-1} and RR values above 76.92-fold compared to the laboratory population.

5 spinosyns: spinosad

The LC_{50} and RR values of *R. dominica* for spinosad are presented in Table 5. The Wufeng population exhibited the highest susceptibility to spinosad, with an LC_{50} of 1.0 μg mL^{-1}. All tested populations was susceptibile to spinosad, with the RR values ranging from 0.10- to 1.90-fold compared with the laboratory population. All tested populations with moderate to high resistance to deltamethrin remained susceptible to spinosad, and those with low deltamethrin resistance were also susceptible when compared with the laboratory population.

6 avermectins & milbemycins: abamectin

The LC_{50} and RR values of *R. dominica* for abamectin are presented in Table 6. The laboratory population exhibited the highest susceptibility to abamectin, with an LC_{50} value of 339 μg mL^{-1}. Regardless of their resistance levels to deltamethrin, all tested *R. dominica* populations showed low resistance to abamectin, with LC_{50} values ranging from 543 to 1,936 μg mL^{-1} and RR values between 1.60- and 5.71-fold compared to the laboratory population.

DISCUSSION

In this study, the susceptibility of *R. dominica* populations with varying levels of resistance to deltamethrin was evaluated against six insecticides representing four different modes of action. Among the most susceptible populations for each insecticide, spinosad required the lowest concentration to achieve an LC_{50} of 1 μg mL^{-1}. Based on LC_{50}, the insecticidal toxicity ranking was as follows: spinosad (1 μg mL^{-1}) > phoxim (6 μg mL^{-1}) > permethrin (60 μg mL^{-1}) > phenothrin (130 μg mL^{-1}) > malathion (141 μg mL^{-1}) > abamectin (339 μg mL^{-1}). Although LC_{50} values varied across insecticides, toxicity ranking alone is insufficient to determine their suitability for warehouse application. The susceptibility of

Table 2. Susceptibility, resistance ratio, and resistance level of *Rhyzopertha dominica* populations to phoxim.

	Phoxim (1B organophosphates[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	22 (15–34)	1.30	24.7 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	25 (16–42)	0.70	15.1 (13)	1.14	Low	6.38	Low
Tongxiao	450	100 (46–523)	0.67	25.5 (13)	4.55	Low	7.60	Low
Tongluo	450	7 (4–13)	1.88	21.1 (13)	0.32	Low	10.31	Moderate
Yuanli	450	18 (10–34)	1.30	61.3 (13)	0.82	Low	48.53	High
Central								
Houli	450	7 (5–11)	1.49	40.7 (13)	0.32	Low	15.19	Moderate
Wufeng	450	34 (20–76)	1.15	49.2 (13)	1.55	Low	> 117.65	High
Shengang	450	56 (35–109)	0.74	6.7 (13)	2.55	Low	9.72	Low
Hemei	450	23 (15–53)	1.36	21.6 (13)	1.05	Low	> 117.65	High
Lukang	450	31 (23–42)	1.22	18.8 (13)	1.41	Low	> 117.65	High
Southern								
Minxiong	450	33 (21–67)	1.01	14.5 (13)	1.50	Low	> 117.65	High
Liujiao	450	59 (22–69)	0.86	20.0 (13)	2.68	Low	> 117.65	High
Houbi	450	16 (11–24)	1.51	45.4 (13)	0.73	Low	> 117.65	High
Wandan	450	28 (21–40)	1.05	20.2 (13)	1.27	Low	> 117.65	High
Eastern								
Toucheng	450	6 (3–9)	1.23	31.2 (13)	0.27	Low	2.51	Low
Jiaoxi	450	15 (12–21)	1.02	22.3 (13)	0.68	Low	15.63	Moderate
Dongshan	450	14 (8–28)	0.27	29.3 (13)	0.64	Low	> 117.65	High
Yilan	450	6 (2–8)	1.10	27.1 (13)	0.27	Low	> 117.65	High
Sanxing	450	13 (9–20)	1.23	30.4 (13)	0.59	Low	> 117.65	High
Changbin	450	29 (15–82)	0.95	46.5 (13)	1.32	Low	1.27	Low
Taitung	450	99 (69–164)	1.11	10.3 (13)	4.50	Low	13.20	Moderate

[z] The insecticide mode of action was classified by Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al*. (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

Table 3. Susceptibility, resistance ratio (RR), and resistance level of *Rhyzopertha dominica* populations to permethrin.

	Permethrin (3A pyrethroids[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	659 (452–1,029)	0.76	6.8 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	1,494 (1,169–1,968)	1.26	12.8 (13)	2.27	Low	6.38	Low
Tongxiao	450	1,218 (854–1,806)	1.34	24.0 (13)	1.85	Low	7.60	Low
Tongluo	450	2,678 (1,797–4,786)	1.12	21.8 (13)	4.06	Low	10.31	Moderate
Yuanli	450	2,779 (1,731–5,650)	0.68	17.7 (13)	4.22	Low	48.53	High
Central								
Houli	450	1,963 (1,516–2,669)	0.36	11.0 (13)	2.98	Low	15.19	Moderate
Wufeng	450	> 10,000	-	-	> 15.17	Moderate	> 117.65	High
Shengang	450	3,342 (2,519–4,859)	1.16	13.2 (13)	5.07	Low	9.72	Low
Hemei	450	> 10,000	-	-	> 15.17	Moderate	> 117.65	High
Lukang	450	2,145 (1,342–4,280)	1.19	26.2 (13)	3.25	Low	> 117.65	High
Southern								
Minxiong	450	382 (301–485)	1.28	7.7 (13)	0.58	Low	> 117.65	High
Liujiao	450	1,240 (999–1,557)	1.44	20.5 (13)	1.88	Low	> 117.65	High
Houbi	450	1,498 (1,058–2,247)	0.22	25.0 (13)	2.27	Low	> 117.65	High
Wandan	450	> 10,000	-	-	> 15.17	Moderate	> 117.65	High
Eastern								
Toucheng	450	1,924 (1,521–2,528)	1.29	20.6 (13)	2.92	Low	2.51	Low
Jiaoxi	450	> 10,000	-	-	> 15.17	Moderate	15.63	Moderate
Dongshan	450	2,642 (2,044–3,642)	1.28	21.3 (13)	4.01	Low	>117.65	High
Yilan	450	> 10,000	-	-	> 15.17	Moderate	>117.65	High
Sanxing	450	3,985 (2,867–6,302)	1.16	14.3 (13)	6.05	Low	>117.65	High
Changbin	450	60 (34–94)	1.22	28.5 (13)	0.09	Low	1.27	Low
Taitung	450	329 (124–945)	0.98	75.1 (13)	0.50	Low	13.20	Moderate

[z] The insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al*. (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

Table 4. Susceptibility, resistance ratio (RR), and resistance level of *Rhyzopertha dominica* populations to phenothrin.

	Phenothrin (3A pyrethroids[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	130 (100–173)	1.17	16.8 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	> 10,000	-	-	> 76.92	High	6.38	Low
Tongxiao	450	> 10,000	-	-	> 76.92	High	7.60	Low
Tongluo	450	> 10,000	-	-	> 76.92	High	10.31	Moderate
Yuanli	450	> 10,000	-	-	> 76.92	High	48.53	High
Central								
Houli	450	> 10,000	-	-	> 76.92	High	15.19	Moderate
Wufeng	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Shengang	450	> 10,000	-	-	> 76.92	High	9.72	Low
Hemei	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Lukang	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Southern								
Minxiong	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Liujiao	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Houbi	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Wandan	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Eastern								
Toucheng	450	> 10,000	-	-	> 76.92	High	2.51	Low
Jiaoxi	450	> 10,000	-	-	> 76.92	High	15.63	Moderate
Dongshan	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Yilan	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Sanxing	450	> 10,000	-	-	> 76.92	High	> 117.65	High
Changbin	450	> 10,000	-	-	> 76.92	High	1.27	Low
Taitung	450	> 10,000	-	-	> 76.92	High	13.20	Moderate

[z] The insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al*. (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

Table 5. Susceptibility, resistance ratio (RR), and resistance level of *Rhyzopertha dominica* populations to spinosad.

	Spinosad (5 spinosyns[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	10.2 (5.1–17.6)	0.79	36.2 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	5.3 (2.4–12.9)	0.73	39.5 (13)	0.52	Low	6.38	Low
Tongxiao	450	3.9 (2.6–5.7)	1.30	31.1 (13)	0.38	Low	7.60	Low
Tongluo	450	4.0 (2.1–7.9)	1.03	45.1 (13)	0.39	Low	10.31	Moderate
Yuanli	450	6.8 (4.1–11.7)	1.03	32.8 (13)	0.67	Low	48.53	High
Central								
Houli	450	1.2 (0.6–2.2)	1.03	30.4 (13)	0.12	Low	15.19	Moderate
Wufeng	450	1.0 (0.7–1.5)	0.88	17.1 (13)	0.10	Low	> 117.65	High
Shengang	450	5.3 (4.1–6.9)	1.17	15.8 (13)	0.52	Low	9.72	Low
Hemei	450	11.4 (7.6–18.6)	0.68	20.0 (13)	1.12	Low	> 117.65	High
Lukang	450	17.3 (8.6–50.8)	0.91	62.0 (13)	1.70	Low	> 117.65	High
Southern								
Minxiong	450	9.6 (5.5–19.4)	0.80	23.5 (13)	0.94	Low	> 117.65	High
Liujiao	450	19.4 (11.8–37.4)	0.62	26.2 (13)	1.90	Low	> 117.65	High
Houbi	450	5.8 (3.7–9.2)	1.22	27.4 (13)	0.57	Low	> 117.65	High
Wandan	450	11.2 (6.4–22.8)	0.96	32.9 (13)	1.10	Low	> 117.65	High
Eastern								
Toucheng	450	4.5 (3.1–6.5)	1.42	29.6 (13)	0.44	Low	2.51	Low
Jiaoxi	450	10.8 (4.9–33.4)	0.74	39.4 (13)	1.06	Low	15.63	Moderate
Dongshan	450	5.5 (2.6–12.6)	0.85	40.3 (13)	0.54	Low	> 117.65	High
Yilan	450	8.7 (6.5–11.9)	0.99	15.9 (13)	0.85	Low	> 117.65	High
Sanxing	450	3.0 (1.6–5.7)	0.95	37.8 (13)	0.29	Low	> 117.65	High
Changbin	450	16.5 (8.8–39.8)	0.62	21.4 (13)	1.62	Low	1.27	Low
Taitung	450	4.1 (2.7–6.1)	0.73	24.4 (13)	0.40	Low	13.20	Moderate

[z] The insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al*. (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

Table 6. Susceptibility, resistance ratio (RR), and resistance level of *Rhyzopertha dominica* populations to abamectin.

	Abamectin (6 avermectins & milbemycins[z])						Deltamethrin (3A pyrethroids)[y]	
Population	N[x]	LC_{50} (95% FL[w]) μg mL^{-1}	Slope	χ^2 (*df*)	RR[v]	Resistance level[u]	RR	Resistance level
Laboratory	450	339 (271–429)	1.56	9.7 (13)	1.00	Low	1.00	Low
Northern								
Yangmei	450	1,036 (828–1,314)	1.26	14.3 (13)	3.06	Low	6.38	Low
Tongxiao	450	1,441 (926–1,597)	1.20	27.6 (13)	4.25	Low	7.60	Low
Tongluo	450	543 (431–658)	0.44	21.9 (13)	1.60	Low	10.31	Moderate
Yuanli	450	961 (782–1,184)	1.41	10.3 (13)	2.83	Low	48.53	High
Central								
Houli	450	762 (640–895)	1.82	5.7 (13)	2.25	Low	15.19	Moderate
Wufeng	450	581 (448–717)	1.38	3.8 (13)	1.71	Low	> 117.65	High
Shengang	450	1,542 (1,117–2,426)	1.48	22.8 (13)	4.55	Low	9.72	Low
Hemei	450	975 (811–1,175)	1.58	15.7 (13)	2.88	Low	> 117.65	High
Lukang	450	840 (690–1,014)	1.56	13.2 (13)	2.48	Low	> 117.65	High
Southern								
Minxiong	450	1,418 (941–2,722)	1.05	24.5 (13)	4.18	Low	> 117.65	High
Liujiao	450	1,791 (1,454–2,356)	0.40	7.1 (13)	5.28	Low	> 117.65	High
Houbi	450	754 (572–961)	1.15	7.2 (13)	2.22	Low	> 117.65	High
Wandan	450	1,798 (1480–2,321)	1.74	11.4 (13)	5.30	Low	> 117.65	High
Eastern								
Toucheng	450	1,454 (1,142–1,986)	1.21	12.5 (13)	4.29	Low	2.51	Low
Jiaoxi	450	915 (723–1,157)	1.24	19.7 (13)	2.70	Low	15.63	Moderate
Dongshan	450	1,910 (1,453–2,863)	1.17	18.0 (13)	5.63	Low	> 117.65	High
Yilan	450	1,391 (625–1,689)	1.10	25.5 (13)	4.10	Low	> 117.65	High
Sanxing	450	853 (702–1,023)	1.67	11.8 (13)	2.52	Low	> 117.65	High
Changbin	450	1,244 (526–1,268)	0.71	39.9 (13)	3.67	Low	1.27	Low
Taitung	450	1,936 (1,536–2,662)	1.38	14.3 (13)	5.71	Low	13.20	Moderate

[z] The insecticide mode of action was classified by the Insecticide Resistance Action Committee (IRAC).
[y] The RR values and resistance levels of *R. dominica* to deltamethrin were compiled from Feng *et al*. (2025).
[x] Number of *R. dominica* adults tested.
[w] Estimated lethal concentration values with fiducial limits (FL).
[v] Resistance ratio (RR) = LC_{50} of each population divided by LC_{50} of laboratory population.
[u] Level of resistance was classified as low for RR ≤ 10, moderate for 10 < RR ≤ 40, high for 40 < RR ≤ 160 and extremely high for RR > 160.

deltamethrin-resistant field populations to each insecticide must also be considered. Despite variability in resistance levels, most tested populations were susceptible to malathion, phoxim, spinosad, and abamectin compared to laboratory population, supporting their potential use as alternative insecticides for managing deltamethrin-resistant *R. dominica* populations.

Malathion was initially recommended in 1971 as a replacement for lindane for rice-mixing applications to control stored-product pests in Taiwan (Lin 1972). However, by 1979, the emergence of malathion resistance in stored-product pests led to its replacement by phoxim as the primary insecticide (Wang & Ku 1981). Although malathion remains on the current list of recommended insecticides, it is no longer used for rice-mixing applications in practice. In this study, most *R. dominica* populations were found to be susceptible to malathion compared with the laboratory population, suggesting a decline in malathion resistance over time. Although five populations (Yangmei, Tongluo, Hemei, Yilan, and Sanxing) still exhibited relatively higher LC_{50} values than the 887 μg mL^{-1} reported for the Kuanyin population by Yao & Lo (1994), the overall trend suggests a substantial reversion toward susceptibility. Nevertheless, according to the current formulation and dilution recommendation, the amount of active ingredient applied is approximately 66.7 μg per 10 g of paddy rice, which represents only 0.47 times the LC_{50} value obtained for the most susceptible population (Toucheng) in this study. Therefore, while reintroducing malathion as a rice-mixing insecticide could be a feasible strategy for managing deltamethrin-resistant *R. dominica* populations, an increase in the application rate would likely be required to achieve effective control.

Phoxim was introduced in 1979 for rice-mixing applications to control stored-product pests in Taiwan. However, its continuous use over 2 decades (1979–1999) led to the development of resistance to phoxim in major stored-product pests such as *R. dominica* and *Sitotroga cerealella* (Olivier) (Kao & Tzeng 1992; Yao & Lo 1994, 1995). In response, deltamethrin replaced phoxim in 2002 as the primary insecticide for use in warehouses. Although phoxim is still listed as a recommended insecticide for empty-warehouse disinfection, it has not been used in rice mixing for over 25 years. This prolonged suspension may have contributed to the observed reduction in phoxim resistance. In this study, all tested populations were more susceptible to phoxim than the laboratory population. The Tongxiao population, the most tolerant assessed, had an LC_{50} that was 0.11-fold lower than that of the Kuanyin population reported by Yao & Lo (1994). This finding indicates a substantial reversion toward susceptibility following long-term non-use. However, as phoxim is currently not included on the list of recommended insecticides for rice-mixing, re-registration may be required to enable its use in stored-product pest management in the future.

Spinosad is currently not listed among the recommended insecticides for use in warehouses in Taiwan. However, it has been considered an effective candidate for controlling deltamethrin-resistant *R. dominica* (Chen & Chen 2013; Ramesh Babu *et al*. 2017b). Chen & Chen (2013) reported that deltamethrin-resistant *R. dominica* populations remained susceptible to spinosad, with a maximum resistance ratio of 2.7 and an LC_{50} of 0.264 mg kg^{-1} observed in the Minshong population in Taiwan. In this study, all field populations exhibited lower resistance to spinosad than the laboratory population. Resistance ratios ranged from 0.10 to 1.90, and the highest LC_{50} value (1.94 mg kg^{-1}) was recorded in the Liujiao population. However, when compared with the Minshong population documented by Chen & Chen (2013), the highest LC_{50} observed in this study represents a 7.35-fold increase, indicating a measurable upward shift in spinosad tolerance. Although spinosad and deltamethrin act through different modes of action, Wang *et al*. (2025) confirmed that there was no cross-resistance between spinosad and other insecticides, including malathion (1B), deltamethrin (3A), imidacloprid

(4A), bensultap (14), and chlorantraniliprole (28). Nonetheless, previous studies have indicated the potential for cross-resistance in Hemiptera and Lepidoptera insects (Ishtiaq *et al*. 2012; Banazeer *et al*. 2019). For example, *Spodoptera exigua* (Hübner) strains selected for deltamethrin resistance exhibited moderate resistance to spinosad (Ishtiaq *et al*. 2012), while *Phenacoccus solenopsis* Tinsley population resistant to spinosad also showed resistance to deltamethrin and profenofos (Banazeer *et al*. 2019). These findings suggest that the inclusion of spinosad in insecticide rotation strategies should be accompanied by resistance monitoring and assessment of potential cross-resistance with 1B organophosphates and 3A pyrethroids.

Abamectin is also currently not listed among the recommended insecticides for use in warehouses in Taiwan. However, its potential efficacy against *R. dominica* on several cereal commodities has been demonstrated in previous studies (Kavallieratos *et al*. 2009; Perišić *et al*. 2020). Kavallieratos *et al*. (2009) reported 73.9% mortality of *R. dominica* after 14 d of exposure to abamectin at an application rate of 0.1 mg kg^{-1} on wheat at 30℃, with mortality increasing to 99.4% when the application rate was raised to 0.5 mg kg^{-1}. Similarly, Perišić *et al*. (2020) found that application rates of 0.5–1 mg kg^{-1} on wheat resulted in 67–85% mortality after 14 d, and that complete mortality was achieved at an application rate as low as 0.25 mg kg^{-1} when the exposure duration was extended to 21 d at 26℃. Although both studies evaluated an application rate of 0.5 mg kg^{-1} on wheat, differences in observed mortality after 14 d of exposure were evident. Such variation likely reflects differences in experimental conditions, including temperature, as well as commodity-related factors such as cereal cultivar. Although abamectin has demonstrated efficacy against *R. dominica* on wheat and other cereal commodities, its effectiveness on paddy rice has not yet been evaluated. Consequently, further studies are required to assess the efficacy and practical applicability of abamectin for controlling *R. dominica* under warehouse conditions.

In contrast to the promising alternative insecticides discussed above, permethrin and phenothrin were unsuitable for controlling deltamethrin-resistant *R. dominica*. For permethrin, although only five populations exhibited moderate resistance relative to the laboratory population, the LC_{50} values of the Wufeng, Hemei, Wandan, Jiaoxi, and Yilan populations exceeded 10,000 mg mL^{-1}. These LC_{50} values represent a more than 26.8-fold increase compared with the Kuanyin population reported by Yao & Lo (1994). When compared with the most susceptible population (Changbin) in this study, these four populations demonstrated more than a 166.67-fold increase in LC_{50}, indicating extremely high levels of resistance. Although permethrin remains listed as a recommended insecticide for empty-warehouse disinfection in Taiwan, the elevated LC_{50} values observed here suggest that its continued use may no longer be effective for managing *R. dominica*.

For phenothrin, all tested populations exhibited high levels of resistance, with resistance ratios exceeding 76.9 when compared to the laboratory population. Phenothrin and deltamethrin both belong to the 3A pyrethroid and share the same mode of action by targeting voltage-gated sodium channels in the insect nervous system. This similarity in mode of action suggests a strong likelihood of cross-resistance among insecticides within this insecticide group. Previous studies have reported that deltamethrin-resistant *R. dominica* populations were concurrently resistant to permethrin (Lorini & Galley 2001), further reinforcing the limited utility of pyrethroids as alternative insecticides for managing deltamethrin-resistant populations.

Insecticide rotation is a critical strategy for managing insecticide-resistant pest populations (Madgwick & Kanitz 2024). However, only two insecticides, deltamethrin and malathion, are currently recommended for rice-mixing applications to control stored-product pests in Taiwan. Among these, malathion is no longer used in practice due to the historical development of resistance in stored-product pests, thereby limiting the feasibility of rotation-based resistance management in paddy rice warehouses in Taiwan. In this study, all tested *R. dominica* populations exhibited susceptibility to four insecticides- malathion, phoxim, spinosad, and abamectin, when compared with the laboratory population under controlled conditions. Nevertheless, actual warehouse trials are required to further evaluate the efficacy of these insecticides in controlling stored-product pests and to determine the appropriate operational dosages under field conditions. To reduce reliance on insecticides with a single mode of action, it is essential to gradually expand the number of insecticides approved for rice-mixing in warehouses. Given that malathion remains on the recommended list for rice-mixing to control *R. dominica* in paddy rice warehouses in Taiwan, forthcoming evaluations will prioritize testing higher application dosages to determine achievable control performance and compliance with residue standards.

In addition to exploring alternative insecticides, incorporating non-chemical controls such as improved ventilation, light traps, and pheromone traps into pest management programs can further strengthen resistance management. Establishing a science-based, integrated strategy that combines insecticides with multiple modes of action and complementary non-chemical controls, specifically tailored to Taiwan's storage systems, will be crucial for delaying the development of resistance and ensuring the long-term effectiveness of recommended insecticides.

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第滅寧抗藥性穀蠹（鞘翅目：長蠹蟲科）對替代殺蟲劑之感受性評估

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摘要

馮文斌、李啟陽、姚美吉。2026。第滅寧抗藥性穀蠹（鞘翅目：長蠹蟲科）對替代殺蟲劑之感受性評估。台灣農業研究 75(2):249–263。

穀蠹 (*Rhyzopertha dominica* (Fabricius)) 為臺灣稻穀倉庫中的重要害蟲。自 2002 年起，第滅寧即為倉庫中稻穀混拌處理所推薦使用的主要殺蟲劑，惟長期使用已導致田間族群普遍產生抗性，特別是在臺灣中部與南部地區。為尋找具潛力之替代藥劑，本研究針對 20 個具不同第滅寧抗藥性程度之穀蠹田間族群，評估其對 4 種不同作用機制之 6 種殺蟲劑的感受性，包括 1B 有機磷類：馬拉松與巴賽松；3A 除蟲菊類：百滅寧與撲滅芬；5 賜諾司類：賜諾殺；以及 6 阿維菌素類 & 米爾貝黴素：阿巴汀。透過稻穀混拌法進行之實驗室生物檢定結果顯示，相較於實驗室敏感品系，大多數族群對馬拉松、巴賽松、賜諾殺及阿巴汀保持感受性。相較之下，所有受測族群皆對撲滅芬呈現高度抗性；另雖部分族群相對於實驗室品系僅呈現中度百滅寧抗性，但其半致死濃度值均超過 10,000 μg mL^{-1}，顯示其田間應用價值極為有限。綜合結果顯示，馬拉松、巴賽松、賜諾殺及阿巴汀具有作為第滅寧抗性穀蠹防治替代藥劑之潛力。後續仍需透過田間試驗驗證其實際防治效果，並確立於實際操作條件下的適宜施用劑量，以支持未來登記使用與建立倉庫稻穀殺蟲劑輪用之科學化管理策略。

關鍵詞：穀蠹、替代殺蟲劑、半致死濃度、抗性比、殺蟲劑抗性程度。

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