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THE ROLE OF SOME INSECT GROWTH REGULATORS IN CONTROLLING SOME WAREHOUSE INSECTS

Naseer Malaky Abbood
Thi -Qar Education Directorate, Ministry of Education, Thi -Qar, Iraq
E-mail: Naseer.abood@sci.utq.edu.iq

Abstract. This study aimed to evaluate the efficacy of three insect growth regulators (IGRs) (Lufenuron, Novaluron, and Triflumuron) at a sublethal concentration (0.003 mg/L) in inhibiting and destroying the physiological parameters and fitness of the stored date moth (Cadra cautella) and the raisin moth (Cadra calidella) reared on three different food hosts (industrial medium, dates, and figs). The results showed that all tested regulators significantly increased the mean pupal stage and severely inhibited the emergence rate of adult moths compared to the control treatments. The derived physiological parameters revealed a significant deterioration in the growth rate index (DVI) and the composite fitness index (BFI). C. cautella exhibited higher sensitivity to the inhibitors compared to C. calidella, which showed relative physiological resistance. The natural food host (especially figs) also worked synergistically with the inhibitors' effectiveness in reducing the life performance of the two insects, thus recommending the integration of these regulators into Integrated Pest Management (IPM) programs for stored materials.

Key words: Cadra cautella, C. calidella, IGRs, Fitness Cost

Introduction

Pests of stored goods are among the greatest challenges to global food security and post-harvest economics. The stored date moth, Cadra cautella (Walker), and the raisin moth, Cadra calidella (Guénée), are particularly notorious as serious pests attacking dates, dried fruits, nuts, and grains in warehouses and warm environments [1]. The economic damage caused by these two species is not limited to the direct consumption of stored goods by the larvae, but also includes the contamination of food products with molted skins, excrement, and the dense silken webbing secreted by the larvae, which reduces the market value of the products and renders them unfit for human consumption [2].

For decades, pest control strategies have relied almost entirely on phosphine, organophosphorus compounds, and synthetic pyrethroids. However, this intensive and unregulated use has led to serious environmental and health consequences, including contamination of stored materials with toxic chemical residues, poisoning of warehouse workers, and, most importantly, disruption of the ecological balance and the emergence of insect strains exhibiting severe physiological and behavioral resistance to conventional pesticides [3]. As a result, there is an urgent need to develop and research environmentally safe and more targeted alternatives that are compatible with integrated pest management (IPM) programs [4]. Insect growth regulators (IGRs) represent an advanced generation of chemical biological control agents. These compounds are classified, based on their mechanism of action, into juvenile hormone mimetics, molting hormone antagonists, and chitin synthesis inhibitors [5]. The compounds tested in this study (Lufenuron, Novaluron, Triflumuron) are among the most prominent chitin synthesis inhibitors belonging to the benzoylphenyl ureas group. The precise physiological mechanism of these compounds lies in their ability to interfere with the chitin synthase enzyme or prevent the incorporation of the precursor compound (N-acetylglucosamine) into the chitin-forming polymer chains during the formation of the new insect cuticle [6]. This inhibition leads to the inability of larvae and pupae to shed the old cuticle during molting, resulting in inevitable deaths, or the emergence of physiologically deformed adults suffering from a severe decline in vital and reproductive capabilities (Fitness Cost) [7]. Studying the effect of sublethal concentrations of growth regulators is of great importance in insect physiology; it allows understanding the long-term cumulative effects of the compound on subsequent generations of the pest without the need to cause immediate mechanical killing, thus reducing the amount of pesticides released into the storage environment [8]. Furthermore, studying the role of the host diet has vital practical applications, as the host's nutritional components—carbohydrates, proteins, lipids, and sterols—directly affect the efficiency of the insect's immune system and its ability to produce detoxification enzymes such as cytochrome P450 and glutathione [9]. This study aimed to:

1. Evaluate the biological and physiological efficacy of a sublethal concentration (0.003 mg/L) of three insect growth regulators (triflumuron, novaluron, and lufenuron) in prolonging the pupal stage and inhibiting adult emergence in C. cautella and C. calidella .

2. Determine the synergistic effect between the type of host diet (industrial environment, dates, figs) and the action of the growth regulators in suppressing the life cycle of the two insects.

3. Calculation and extrapolation of composite derived parameters (DVI, BFI, RASR, HPPR, PRCR, SPRI) to characterize physiological deterioration and calculate the expected reduction in reproductive capacity of future generations, and isolate qualitative differences in natural resistance between the two targeted insects.

Materials and Methods

Laboratory Environment and Culture:

The experiments were conducted in a specialized laboratory in an incubator at a temperature of 25°C ± 3°C and a relative humidity of 45% ± 10%, with periodic replacement of cultures to maintain viability. Three food hosts were tested: an artificial medium (88 g cracked wheat, 12 ml glycerin, 1 g dry yeast), dates, and figs.

Treatment and Calculation of Parameters:

Firstly, the effect of insect growth regulators (Triflumeron, Novaluron, and Lufenuron) on some vital parameters of the stored date moth and the raisin moth. Eggs of the two insects, reared on three food media (artificial medium consisting of 88 g of cracked wheat, 12 ml of glycerin, and 1 g of dry baker's yeast, dates, and figs), were treated with a sublethal concentration (0.003mg/ L) of the aforementioned inhibitors. It is worth noting that this concentration was determined in previous studies. The eggs were treated using a small 5 ml sprayer, with five replicates of 30 fresh eggs (24-48 hours old) in each replicate. The eggs were placed in a 9 cm diameter Petri dish. After treatment, the treated eggs were transferred to 3 x 6 cm plastic containers containing 5 g of the food medium. The eggs were monitored until the larvae hatched, at which point they were transferred individually. New plastic rearing containers contain food medium were used to measure the pupal stage and the adult insect emergence rate. The adult insects were then isolated in special funnel-shaped glass containers with a sugar-water food solution to measure their survival time. The following vital parameters were calculated: average pupal stage period (in days), average adult emergence rate (%) for both the stored date moth and the raisin moth, and the Developmental Velocity Index (DVI), which calculates the biological rate of pupal development per day using the equation [10]:

$$DVI = \frac{1}{\text{Mean Pupal Duration (days)}}$$

The Bio-Fitness Index (BFI), a composite index linking (pupa growth rate) and (adult emergence success) into a single number, was also calculated to give a comprehensive assessment of the suitability of the insect host under the influence of the inhibitor, using the equation [11]:

$$BFI = \frac{\text{Adult Emergence }\%}{\text{Mean Pupal Duration (days)}}$$

The Relative Adult Survival Rate (RASR) was also calculated, which determines the extent of the deterioration of the Fitness Cost through the equation [12]:

$$RASR = \frac{\%\ \text{Emergence in Treatment}}{\%\ \text{Emergence in Control}}$$

Values close to 1 indicate no effect, while closer to zero indicates damage to the insect's vitality.

The Host-Plant Performance Ratio (HPPR), which isolates the effect of "food type," was also calculated to determine which natural host (dates or figs) was more stressful for the insect compared to the artificial environment, using a natural environmental baseline (Baseline = 1.00) under the influence of inhibitors, as calculated using the equation: [13]:

$$HPPR = \frac{\text{BFI (Natural Host: Date or Fig)}}{\text{BFI (Artificial Diet)}}$$

Values less than 1.00 indicate that the food source imposes additional synergistic stress, reducing the insect's vital performance.

The Predicted Reproductive Capacity Reduction (PRCR) was also calculated, which predicts a decrease in the reproductive capacity of adults emerging from treated pupae [14]:

$$PRCR = \left(\frac{1 - BFI\ Treatment}{BFI\ Control}\right) \times 100$$

As for the (Species Physiological Resistance Index - SPRI) criterion, which isolates the differences between species (stored date moth vs. raisin moth) to determine which of the two species possesses "natural resistance" or a higher ability to tolerate inhibitors across all food environments (taking the stored date moth as a baseline = 1.00), it was calculated from the following equation:

$$SPRI = \frac{\text{BFI of } \textit{Cadra figulilella}}{\text{BFI of } \textit{Cadra cautella}}$$

Where values higher than 1.00 mean that the raisin moth is more resistant and tolerant to the IGR than the stored date moth in that treatment

Statistical Analysis:

Laboratory experiments for all treatments and their interactions were conducted using a completely randomized design (CRD) with a factorial experiment involving three factors: insect growth regulators, target insect species, and food host. All obtained data (pupa period and adult emergence rate) were subjected to analysis of variance (ANOVA) using the SPSS statistical software. To determine the significance of differences between the means of treatments and two-way and three-way interactions at a probability level ($P \leq 0.05$), Duncan's Multiple Range Test was applied (where means with significant differences were coded with different letters, while non-significant means were coded with the same letters) .

Results and Discussion

First: The Pupal Stage

The statistical results in Table 1 showed a clear significant effect ($P \leq 0.05$) of all tested insect growth regulators on lengthening the pupal stage of the two insects compared to the control treatment, which recorded the shortest pupal stage period of 6.75 days and 7.00 days on the artificial environment of the date moth and the raisin moth, respectively. The growth regulator Novaluron demonstrated absolute superiority in inducing physiological elongation, with an overall average duration of pupal elongation of 13.08 days, followed by Triflumuron (11.12 days) and Lufenuron (10.41 days). This marked physiological prolongation is attributed to the delayed action of chitin synthesis inhibitors; sublethal concentrations do not lead to immediate death, but rather interfere with hormonal regulation by inhibiting the secretion of molting hormone (ecdysone) or disrupting the balance between it and juvenile hormone. Consequently, under chemical stress, the pupa is forced to extend this critical physiological phase in an attempt to complete the repair of structural damage and synthesize the skin proteins necessary for the formation of a healthy adult, which depletes its stores of fat bodies and stored energy. Regarding the effect of insect species and host plant, the raisin moth C. calidella (average 11.93 days) exhibited longer elongation periods than the date moth C. cautella (9.60 days). Examining host interaction, we found that natural hosts (dates and figs) significantly increased development periods when combined with an insect growth regulator compared to the artificial environment. For example, the raisin moth treated with Novaluron on the date host recorded a maximum growth period of 15.5 days. This is physiologically explained by the fact that the improved artificial environment contains standardized high levels of proteins, essential fatty acids and vitamin B (from yeast and grits) that give the insect compensatory energy and physiological resistance that enable it to accelerate the pace of metabolism and decompose toxins, while the natural hosts impose nutritional stress that chemically and biologically synergizes with the effect of the growth regulator, thus prolonging the period of suffering and growth of the pupal stage.

Second: The percentage of adult insects emerging

The results in (Table 2) showed that the tested insect growth regulators caused a sharp and significant reduction in the percentage of live adults emerging from pupae resulting from eggs treated with a concentration of 0.003 mg/L of IGRs compared to the control treatments, whose normal emergence rates ranged between 85% and 90% (the overall average for the control was 85.83%). The growth regulator Novaluron proved to be of superior efficiency in preventing external insect metamorphosis, as the overall average percentage of adults emerging under its influence decreased to 45.83%, followed by (60.83%) Triflumuron and (61.66%) Lufenuron. The mechanism of this physiological failure to emerge is due to the inability of the internally formed adults to rupture and burst the pupal case wall. The adult insect's emergence relies on hemolymph pressure and mechanical movement to rupture the pupal shell at the middorsal line. Under the influence of chitin inhibitors, the pupal shell becomes brittle or extremely rigid and inflexible due to defects in chitin and sclerotin protein inlays. This leads to the adult insect becoming trapped and dying partially or completely inside the pupal shell, or emerging with deformed and wrinkled wings incapable of flight or mating. Regarding the combined synergistic effect of the plant host, the results revealed a very sharp and significant decrease in the emergence rate of the date moth, C. cautella, when treated with Triflumuron on the date host, reaching only 15%, and with Novaluron on the fig host, reaching 30%. This sharp decline confirms the strong synergy between the growth regulator and the natural food environment. The deficiency of certain vital substances, such as sterols, which the insect cannot synthesize itself and which are precursors to molting hormones, in the date and fig hosts, compared to the artificially enhanced environment, leads to a complete paralysis of the insect's physiological system. This enhances the biological lethality of the regulators, even at sublethal concentrations [15].

Table 1. Effect of insect growth regulator and food host type on the average pupal stage period (days) of the stored date moth Cadra cautella and the raisin moth Cadra calidella

Overall IGR mean	Fig	Dates	Artificial medium	Insect species	IGRs
11.12 b	9.75 e f	9.75 e f	11.00 c f	Stored date moth	Triflumuron
	10.75 d f	13 .00 a c	13 .00a c	Raisin moth	
13.08 a	12 .00 b e	12.75 b d	11.5 0 b e	Stored date moth	Novaluron
	13.00 a c	15.50 a	13.75 a b	Raisin moth	
10.41 b	9.75 e f	8.25 f g	10.50 c f	Stored date moth	Lufenuron
	11.5 0 b e	10.50 c f	12.00 b e	Raisin moth	
8.45 c	6.75 g	6.75 g	7 .00 h g	Stored date moth	Control
	9.50 e f h	10.00 d f	10.75 c f	Raisin moth	
	10.37 a *	10.81 a *	11.12 a *		Overall mean of interactions
			9.60 b	Stored date moth	The overall mean for the insect species
			11.93 a	Raisin moth	

- Significance test: Means marked with different letters within the same column or row differ significantly at a probability level of ($P \leq 0.05$).
- Mark: (*) Comparisons marked with an asterisk in the overall mean of food environments indicate a clear and significant interaction between host type and insect growth regulator efficiency.

Table 2. Effect of insect growth regulator and food host type on the average adult emergence percentage (%) of the stored date moth Cadra cautella and the raisin moth Cadra calidella

Overall IGR mean	Fig	Dates	Artificial medium	Insect species	IGRs
60.83 b	45 .00 a b	55.00 a d	60 .00 a e	Stored date moth	Triflumuron
	70.00 b e	65.00 b e	70 .00 b e	Raisin moth	
45.83 c	30 .00 a	50.00 a c	45 .00 ab	Stored date moth	Novaluron
	40 .00 ab	60 .00 a e	50 .00 a c	Raisin moth	
61.66 b	40 .00 ab	65 .00 b e	70 .00 b e	Stored date moth	Lufenuron
	45 .00 a b	80 .00 c e	70 .00 b e	Raisin moth	
85.83 a	80 .00 c e	85 .00 d e	85 .00 d e	Stored date moth	Control
	90 .00 e	90 .00 e	85 .00 d e	Raisin moth	
	55.00 b *	68.75 a *	66.87 a *		Overall mean of interactions
			59.16 b	Stored date moth	The overall mean for the insect species
			67.91 a	Raisin moth	

- Significance test: Means marked with different letters within the same column or row differ significantly at a probability level of (P ≤ 0.05).
- Mark: (*) Comparisons marked with an asterisk in the overall mean of food environments indicate a clear and significant interaction between host type and insect growth regulator efficiency.

Third: Derived and Composite parameters:

Table 3 includes several vital parameters derived from Tables 2 and 3:

Developmental Velocity Index (DVI): The biological rate of development decreased significantly from 14.28%–14.81% in the normal control treatments, dropping to its lowest physiological levels under the influence of Novaluron 6.45% for both the date palm moth on dates and the raisin moth on dates. This sharp slowdown in growth rate effectively prolongs the insect generation within storage facilities, thus reducing the number of annual generations of the pest and preventing population explosions [16].

Bio-Fitness Index (BFI): This index recorded a dramatic and comprehensive collapse; while in the control medium it ranged between 7.90 and 12.59, reflecting ideal physical fitness, it declined in the treatments to record its lowest value in the date moth treated with Novaluron on the fig host at 2.50, and the date at 1.53 under the influence of Triflumuron. This index combines two criteria (speed and success), and therefore its decline reflects a complete destruction of the insect's life efficiency.

Relative adult survival rate and fitness cost (RASR): This value showed a sharp approach to zero in certain treatments, recording 0.18 for the date moth with Triflumuron on dates, and 0.37 with Novaluron on figs. Mathematically, the further this value deviates from 1.00, the greater the physiological failure and the higher the fitness cost incurred by the surviving insects, physiologically demonstrating that they are weakened adults suffering from biological sterility.

The host plant performance ratio (HPPR): All values of this criterion have decreased under the baseline (1.00) in both date and fig hosts, reaching 0.61 for the date moth with Lufenuron on figs and 0.63 for the date moth with Novaluron on dates. This demonstrates, both numerically and experimentally, that the natural host provides no protection or physiological support to the insect against growth regulators, but rather acts as a supplementary stressor, diminishing overall performance compared to the artificial environment.

Predictive Reduction in Reproductive Capacity (PRCR): Predictive calculations showed a significant collapse in the expected reproductive capacity of future generations. The decline was most pronounced in the date palm moth treated with Novaluron on fig hosts, reaching 78.90%, and with Triflumuron on dates, reaching 77.06%. The physiological reasons for this expected reduction are attributed to the sublethal effects of chitin inhibitors, which prevent cell division and ovarian tubule formation in ectopic females, or prevent proper sperm transfer in malformed males, leading to the production of unfertilized eggs and severe hatching failure in the next generation.

The Species Physiological Resistance Index (SPRI) revealed a highly significant physiological finding: all SPRI values were above the baseline (1.00) across all treatments and levels. The combined values for the two insects ranged from 1.22 to 1.41 and 1.48 for the three regulators, respectively. This mathematically and scientifically confirms that the raisin moth, C. calidella , possesses a natural physiological resistance and a higher capacity to tolerate and degrade the action of insect growth regulators compared to the stored date moth, C. cautella , across all available nutrient media. This is physiologically attributed to the efficiency and capability of the metabolic detoxification enzyme system of pesticides, such as esterases or cytochrome P450 monooxygenases, in the larvae and pupae of the raisin moth, which enables them to break down growth regulator molecules more effectively and reduce their access to target sites compared to the stored date moth.

Table 3: Effect of insect growth regulators and host type on the Developmental Velocity Index (DVI), Bio-Fitness Index (BFI), Relative Adult Survival Rate (RASR), Host-Plant Performance Ratio (HPPR) The Predicted Reproductive Capacity Reduction (PRCR), and Species Physiological Resistance Index (SPRI) of the stored date moth Cadra cautella and the raisin moth Cadra calidella.

Fig	Dates	Artificial medium	Derived bio-parameter	Insect species	IGRs
10.25%	10.25%	9.09%	(DVI)	Stored date moth	Triflumuron
0.56	0.64	0.70	(RASR)		
4.61	5.64	5.45	(BFI)		
0.84	1.03	baseline (1.00)	HPPR		
61.10%	55.20%	55.10%	PRCR		
9.30%	7.69%	7.69%	(DVI)	Raisin moth	
0.77	0.72	0.82	(RASR)		
6.51	5.00	5.38	(BFI)		
1.21	0.92	baseline (1.00)	HPPR		
27.66%	44.44%	31.89%	PRCR		
1.41	0.88	0.98	SPRI (For both insects together)		
8.33%	7.84%	8.69%	(DVI)	Stored date moth	Novaluron
0.37	0.58	0.52	(RASR)		
2.50	3.92	3.91	(BFI)		
0.63	1.00	baseline (1.00)	HPPR		
78.90%	68.86%	67.79%	PRCR		
7.69%	6.45%	7.27%	(DVI)	Raisin moth	
0.44	0.66	0.58	(RASR)		
3.07	3.87	3.63	(BFI)		
0.84	1.06	baseline (1.00)	HPPR		
67.58%	57.00%	54.05%	PRCR		
1.22	0.98	0.92	SPRI (For both insects together)		
10.25%	12.12%	9.52%	(DVI)	Stored date	Lufenuron

0.50	0.76	0.82	(RASR)	moth	
4.10	7.87	6.66	(BFI)		
0.61	1.18	baseline (1.00)	HPPR		
65.40%	37.49%	45.14%	PRCR		
8.69%	9.52%	8.33%	(DVI)		
0.77	0.88	0.82	(RASR)		
6.08	7.61	5.83	(BFI)		
1.04	1.30	baseline (1.00)	HPPR	Raisin moth	
35.79%	15.44%	26.20%	PRCR		
1.48	0.96	0.87	SPRI (For both insects together)		
14.81%	14.81%	14.28%	(DVI)	Stored date moth	
11.85	12.59	12.14	(BFI)		
10.52%	10.00%	9.30%	(DVI)	Raisin moth	Control
9.47	9.00	7.90	(BFI)		

Conclusions

1. The three insect growth regulators (Novaluron, Triflumuron, and Lufenuron) demonstrated high biological efficacy at sublethal concentrations (0.003 mg/L) in disrupting the life cycle and physiology of stored date moth and raisin moth.
2. The insect growth regulator Novaluron was distinguished by its absolute superiority in prolonging the pupal stage, inhibiting adult emergence rates, and reducing the composite fitness index (BFI).
3. The derived mathematical indices (HPPR) proved that the natural host species (dates and figs) acts as a synergistic stress factor, enhancing the effectiveness of the sublethal compounds compared to the artificial environment.
4. The SPRI index revealed the physiological superiority of the raisin moth in tolerating and resisting the effects of the growth regulators compared to the stored date moth , which exhibited high sensitivity.

Recommendations

1. Adopt the insect growth regulator Novaluron as a primary option within Integrated Pest Management (IPM) programs for the protection of dates and dried fruits.
2. Use sublethal concentrations of IGRs to minimize environmental pollution and control costs, while leveraging their cumulative effects in reducing the reproductive capacity (PRCR) of subsequent generations.
3. Consider the species of stored pest when designing control plans, given the

physiological differences in susceptibility between the date moth and the raisin moth.

4. Conduct future studies to evaluate enzyme activity, such as esterase levels, to determine the precise mechanism of the raisin moth's relative resistance to pesticides.

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Conflict of Interest Statement

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