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RESEARCH

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Influence of temperature on the toxicity and stability of insecticide resistance against *Spodoptera littoralis* (Lepidoptera: Noctuidae)

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Abstract

Background *Spodoptera littoralis* Boisad. (Lepidoptera: Noctuidae) is an important pest causing significant losses to agricultural crops worldwide. Management practices for this insect pest rely on insecticides applications throughout the entire season over wide ranging temperature. However, studies involving the development of resistance in *S. littoralis* against these insecticides at different temperatures are limited.

Methods Using leaf-dipping bioassay technique, the effect of temperature (range, 15–30 °C) on the toxicity of spinosad, lambda-cyhalothrin and methomyl, and resistance development was evaluated in larvae *S. littoralis*.

Results Spinosad, lambda-cyhalothrin and methomyl exhibited increased toxicity with increasing temperature from 15 to 30 °C. The results indicated a successive decrease in insecticide resistance at the temperatures of 15, 20, 25 and 30 °C from 1st to 12th generations of *S. littoralis* to spinosad, lambda-cyhalothrin and methomyl.

Conclusions This study suggests that spinosad, lambda-cyhalothrin, and methomyl can be included in the management of *S. littoralis*.

Highlights

- Toxicity due to lambda-cyhalothrin, methomyl and spinosad exposure increases with increasing temperature.
- Temperature influences the resistance of S. littoralis to lambda-cyhalothrin, methomyl and spinosad.
- Temperature should be integrated into the assessment of both toxicity and insecticide resistance.

Keywords Insecticide resistance, Insecticide toxicity, Temperature coefficient

Background

The cotton leafworm, *Spodoptera littoralis* Boisad. (Lepidoptera: Noctuidae), is a cosmopolitan insect and has gained importance as a major destructive pest owing to its capacity to feed on many a variety of important agricultural crops, and is known to attack more than 80 species of cultivated plants about 40 families in different parts of the world. Infestations lead to inflicts significant economic losses to the yield of quantity and quality

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(Ismail et al. 2020). Due to its wide host range, production of multiple generations per year, high fecundity, migratory behavior and pronounced resistance to many insecticides, the control up to desired level has become difficult (Ismail 2022). The use of insecticides is the main control strategy for this pest however, indiscriminate and extensive use of insecticides has resulted in the development of resistance in many *S. littoralis* populations. Resistance to a wide range of conventional and new chemistry insecticides in *S. littoralis* has been reported worldwide, including Egypt (Ismail et al. 2020).

Environmental conditions, mainly temperature, significantly affect the toxicity of insecticides and thus their efficacy against insects (Neven 2000; Gordon 2005; Deutsch et al. 2018; Ismail 2020). In addition, the life-history traits of organisms, such as feeding rate, growth, and reproduction, may be influenced by temperature as well and also govern the population dynamics (Musser and Shelton 2005; Satpute et al. 2007; Boina et al. 2009; Lekha et al. 2017). Although the effect of temperature on the toxicity of insecticides has been studied in many different species, few studies of this type have been performed on insecticide-resistant strains. Hence, any alteration in resistance levels could be caused by temperature changes, and this needs further investigation (Morytz et al. 1997; Lekha et al. 2017; Deutsch et al. 2018; Zhang et al. 2021). Thus, the objective of this study was to examine the stability of *S. littoralis* resistance to spinosad, lambda-cyhalothrin, and methomyl at different temperatures in the absence of selection pressure, for the purpose of making evidence-based decisions to understand the effect of temperature on insecticide toxicity and resistance.

Methods

Spodoptera littoralis collection and rearing temperature

Egg mass samples of *S. littoralis* were collected from tomato crop in farmers' fields at Egyptian Governorate (El-Dakahlia) during 2021 and brought to laboratory. After hatching, larvae were raised in glass jars in the rearing room at various temperatures—15, 20, 25, and 30 °C, 65 ± 5% relative humidity, and a natural photoperiod (16 h: 8 h L: D)—on leaves of the castor bean (*Ricinus communis* L.) that had not been treated with insecticides. The choice of temperature ranges was based on previous experiment by Ismail (2020). The jars were subject to an exchange of leaves twice a day.

Insecticides

In this experiment, commercial insecticides that have a different mode of action as well as farmers' preference were chosen in Egypt shown as follows in Table 1.

Bioassays

Second instar larvae of *S. littoralis* were treated with Spinosad, lambda-cyhalothrin, and methomyl for toxicological studies at each temperature on 1st, 4th, 8th, and 12th generations. Six experimental groups were conducted using the leaf-dipping technique, along with the control group (insecticide-free leaves) in eight replicates of each treatment. Larvae were handled with a delicate brush for examination, and mortality data were recorded after 48 h for lambda-cyhalothrin and methomyl and 72 h for spinosad.

Data analysis

The probit analysis (POLO-PC Program, LeOra Software LLC, Petaluma, CA, USA) was used to calculated LC_{50} values of each insecticide at each temperature (LeOra 2003). A resistance factor (RF) was calculated according to the method of Wearing and Catherine (2005). A temperature coefficient was calculated for each insecticide, and it is considered positive if the LC_{50} value is low at a higher temperature and negative if the LC_{50} value is low at a lower temperature according to the method of Musser and Shelton (2005).

Results

Spinosad

The spinosyn insecticide spinosad exhibited positively correlated toxicity within the temperature range (15–30 °C) tested (Table 2). The toxicity of spinosad increased by 1.08- to 3.14-fold from 15 to 20 °C and by 2.03- to 2.83-fold from 25 to 30 °C. Similarly, the toxicity values of 4th, 8th and 12th generations of *S. littoralis* showed a positive correlation with temperature. There was a successive decrease in the insecticide resistance from 1st to the 12th generations of *S. littoralis* to spinosad with values of 0.042-, 0.040-, 0.038-, and 0.035-folds at 15, 20, 25 and 30 °C, respectively. The initial LC_{50} value calculated at temperatures range tested in 1st generation were greater as compared with a final LC_{50} values observed in 12th generation, indicating an increase in toxicity.

Table 1 Classification of commercial insecticide formulations in accordance with the active ingredient and manufacturer

Insecticide group	Active ingredient	Commercial insecticide formulation	Form	Manufacturer
Carbamate	Methomyl	Lannate	SP	DuPont, Wilmington, DE, USA
Pyrethroids	Lambda-cyhalothrin	Karate Zeon	EC	Syngenta, Wilmington, DE, USA
Spinosyn	Spinosad	Tracer	SC	Dow AgroSciences, Indianapolis, IN, USA

Table 2 Toxicity of spinosad to different generation of *Spodoptera littoralis* at different constant temperatures

T (°C)[a]	G[b]	n[c]	LC50 and 95% confidence limit (µg/mL)	Slope (± SE)	χ^2 (*df*)	RF[d]	RD[e]	TC[f]		
15	1st	180	18.84 (17.56–20.06)	1.64 (0.50)	0.96 (4)	3.14		5	10	15
	4th	180	17.35 (15.56–19.97)	1.03 (0.32)	0.40 (4)	2.89				
	8th	180	10.28 (5.94–20.41)	1.86 (0.14)	0.84 (4)	1.71				
	12th	180	6.00 (5.60–7.11)	1.30 (0.28)	0.61 (4)		− 0.042			
20	1st	180	16.89 (11.56–21.63)	1.98 (0.11)	1.22 (4)	3.03		1.12		
	4th	180	13.40 (13.05–14.83)	1.86 (0.55)	0.80 (4)	2.40		1.29		
	8th	180	9.36 (7.90–13.28)	1.35 (0.16)	6.17 (4)	1.68		1.10		
	12th	180	5.58 (4.28–7.12)	2.15 (0.29)	1.17 (4)		− 0.040	1.08		
25	1st	180	7.77 (6.23–9.69)	2.66 (0.35)	6.71 (4)	2.83		2.17	2.42	
	4th	180	5.24 (2.56–10.01)	1.18 (0.18)	3.39 (4)	1.91		2.56	3.31	
	8th	180	3.87 (0.92–9.83)	1.46 (0.31)	1.62 (4)	1.41		2.42	2.66	
	12th	180	2.75 (2.21–3.15)	2.78 (0.20)	0.46 (4)		− 0.038	2.03	2.18	
30	1st	180	1.71 (0.85–3.22)	0.75 (0.28)	0.01 (4)	2.63		4.54	9.88	11.01
	4th	180	1.44 (0.52–3.03)	0.77 (0.41)	0.02 (4)	2.22		3.64	9.31	12.05
	8th	180	1.02 (10.97–1.20)	0.30 (0.40)	0.36 (4)	1.57		3.79	9.18	10.08
	12th	180	0.65 (0.62–0.71)	1.35 (0.18)	2.93 (4)		− 0.035	4.23	8.58	9.23

[a] Temperature (°C)

[b] Generation number of *S. littoralis*

[c] Number of larvae *S. littoralis* used in the bioassay including control

[d] Resistance factor was calculated for each generation as LC_{50} of test generation divided by LC_{50} of susceptible generation

[e] Rate of decrease in LC_{50} [log (final LC_{50} – initial LC_{50})/N], where N is number of generation populations reared without insecticide exposure

[f] Temperature coefficient (Ratio of higher to lower LC_{50} value for 5, 10 and 15 °C differences in temperature)

Methomyl

The carbamate insecticide methomyl exhibited positively correlated toxicity within the temperature range (15–30 °C) tested (Table 3). The toxicity of methomyl increased by 1.19- to 4.23-fold from 15 to 20 °C and by 1.61- to 3.86-fold from 25 to 30 °C. Similarly, the toxicity values of 4th, 8th, and 12th generations of *S. littoralis* showed a positive correlation with temperature. From the first to the twelfth generations of *S. littoralis*, there was a progressive decline in the insecticide resistance to methomyl, with values of 0.052, 0.051, 0.049, and 0.048 folds at 15, 20, 25, and 30 °C, respectively. When temperature was increased from 15 to 30 °C, the toxicity of methomyl increased by 3.37-fold, which also resulted in an overall increase in toxicity by 2.41-fold over the entire temperature range tested.

Lambda-cyhalothrin

Lambda-cyhalothrin, a pyrethroid insecticide, displayed positive temperature correlation coefficients, similar to what was shown with the insecticides spinosyn and carbamate (Table 4). With an increase in temperature from 15 to 30 °C, lambda-cyhalothrin toxicity increased positively. Hence, when the temperature was increased from 15 to 30 °C, the toxicity of lambda-cyhalothrin increased by 7.16-fold which also resulted in an overall increase in toxicity values of 4th, 8th, and 12th generations over the entire temperature range tested. There was a successive decrease in the insecticide resistance from 1st to the 12th generations of *S. littoralis* to lambda-cyhalothrin with values of − 0.053, − 0.052, − 0.051, and − 0.050 folds at 15, 20, 25 and 30 °C, respectively.

Discussion

Several studies have reported that temperature affects the toxicity of insecticides and thus their efficacy against insects (Neven 2000; Gordon 2005; Deutsch et al. 2018; Ismail 2020). However, only a few studies are available on the interaction between temperature and insecticides against *S. littoralis*. Hence, the aim this study to define the effects of spinosad, lambda-cyhalothrin, and methomyl against *S. littoralis* at different temperature.

The results indicated that the toxicity of spinosad, lambda-cyhalothrin and methomyl increased with increasing temperature. This indicates an increase in temperature leads to a higher metabolic rate in insects (Scott 1995; Delnat et al. 2021; Zhang et al. 2021).

There was a significant decrease in the LC_{50} with increasing temperature, which is consistent with previous reports of a positive association between temperature

Table 3 Toxicity of methomyl to different generation of *Spodoptera littoralis* at different constant temperatures

T (°C)[a]	G[b]	n[c]	LC50 and 95% confidence limit (μg/mL)	Slope (± SE)	χ^2 (*df*)	RF[d]	RD[e]	TC[f]		
15	1st	180	763.96 (142.24–497.79)	1.23 (0.30)	0.75 (4)	4.23		5	10	15
	4th	180	568.35 (427.54–739.19)	1.14 (0.35)	2.63 (4)	3.15				
	8th	180	347.42 (301.81–339.97)	1.45 (0.40)	0. (4)	1.92				
	12th	180	180.54 (101.82–514.78)	072 (0.10)	0.66 (4)		− 0.052			
20	1st	180	612.60 (513.47–754.18)	2.21 (0.04)	2.81 (4)	4.03		1.25		
	4th	180	403.87 (243.41–675.72)	3.36 (0.19)	0.68 (4)	2.66		1.41		
	8h	180	281.58 (255.1–362.0)	2.58 (0.40)	4.63 (4)	1.85		1.23		
	12th	180	151.99 ((119.61–188.32))	2.42 (0.21)	1.47 (4)		− 0.051	1.19		
25	1st	180	443.67 (324.52–586.94)	1.55 (0.31)	0.31 (4)	3.86		1.38	1.72	
	4th	180	341.13 (248.23–469.34	1.34 (0.13)	0.48 (4)	2.97		1.18	1.67	
	8th	180	224.55 (164.60–334.02)	1.58 (0.15)	5.29 (4)	1.95		1.25	1.55	
	12th	180	114.95 (99.90–129.09)	2.94 (0.47)	0.84 (4)		− 0.049	1.32	1.57	
30	1st	180	266.81 (202.20–333.83)	1.02 (0.11)	2.19 (4)	3.74		1.66	2.30	2.86
	4th	180	155.49 (119.98–193.78)	1.60 (0.19)	2.63 (4)	2.18		2.19	2.60	3.66
	8th	180	93.02 (84.10–104.01)	1.12 (0.71)	0.92 (4)	1.30		2.41	3.03	3.73
	12th	180	71.31 (60.71–83.53)	1.47 (0.65)	2.93 (4)		− 0.048	1.61	2.13	2.53

[a] Temperature (°C)

[b] Generation number of *S. littoralis*

[c] Number of larvae *S. littoralis* used in the bioassay including control

[d] Resistance factor was calculated for each generation as LC_{50} of test generation divided by LC_{50} of susceptible generation

[e] Rate of decrease in LC_{50} [log (final LC_{50} – initial LC_{50})/N], where N is number of generation populations reared without insecticide exposure

[f] Temperature coefficient (Ratio of higher to lower LC_{50} value for 5, 10 and 15 °C differences in temperature)

Table 4 Toxicity of lambda-cyhalothrin to different generation of *Spodoptera littoralis* at different constant temperatures

T (°C)[a]	G[b]	n[c]	LC50 and 95% confidence limit (μg/mL)	Slope (± SE)	χ^2 (*df*)	RF[d]	RD[e]	TC[f]		
15	1st	180	375.75 (283.19–476.81)	1.15 (0.14)	0.56 (4)	4.43		5	10	15
	4th	180	284.12 (183.83–544.86)	1.03 (0.21)	0.49 (4)	3.35				
	8th	180	179.84 (142.14–213.25)	2.73 (0.23)	0.65 (4)	2.12				
	12th	180	84.76 (76.71–93.21)	3.72 (0.48)	0.77 (4)		− 0.053			
20	1st	180	230.81 (167.31–361.60	1.30 (0.19)	5.39 (4)	4.11		1.63		
	4th	180	154.06 (101.82–514.78)	1.79 (0.51)	1.95 (4)	2.74		1.84		
	8th	180	144.19 (128.87–167.76)	3.64 (0.49)	0.85 (4)	2.57		1.25		
	12th	180	56.21 (47.23–56.74)	1.71 (0.16)	4.91 (4)		− 0.051	1.51		
25	1st	180	96.90 (87.56–104.90)	1.92 (0.18)	1.77 (4)	3.84		2.38	3.88	
	4th	180	74.50 (67.16–79.31)	2.16 (0.26)	2.02 (4)	2.95		2.07	3.81	
	8th	180	67.12 (62.32–73.50)	2.25 (0.71)	1.89 (4)	2.66		2.15	2.68	
	12th	180	25.23 (21.39–29.17)	3.70 (0.56)	0.34 (4)		− 0.049	2.23	3.36	
30	1st	180	70.91 (63.11–74.89)	1.50 (0.14)	5.43 (4)	3.63		1.37	3.25	5.30
	4th	180	40.39 (36.98–51.32)	2.11 (0.26)	2.76 (4)	2.10		1.84	3.81	7.03
	8th	180	25.13 (20.94–27.61)	0.55 (0.11)	1.06 (4)	1.29		2.67	5.74	7.16
	12th	180	19.52 (10.47–39.60)	0.99 (0.18)	0.31 (4)		− 0.047	1.29	2.88	4.34

[a] Temperature (°C)

[b] Generation number of *S. littoralis*

[c] Number of larvae *S. littoralis* used in the bioassay including control

[d] Resistance factor was calculated for each generation as LC_{50} of test generation divided by LC_{50} of susceptible generation

[e] Rate of decrease in LC_{50} [log (final LC_{50} – initial LC_{50})/N], where N is number of generation populations reared without insecticide exposure

[f] Temperature coefficient (Ratio of higher to lower LC_{50} value for 5, 10 and 15 °C differences in temperature)

and toxicity of lambda-cyhalothrin, methomyl and spinosad against different insect species such as *Ostrinia nubilalis* (Hübner), *Diaphorina citri* (Kuwayama), *Chrysoperla carnea* (Stephens) and *Earias vitella* (Fabricius) (Musser and Shelton 2005; Satpute et al. 2007; Boina et al. 2009; Mansoor et al. 2015). An important finding of this study is that the degree of resistance to spinosad, lambda-cyhalothrin and methomyl is influenced by the temperature at which the larvae are tested. There was a successive decrease in the insecticide resistance from 1st to the 12th generations, indicating decrease in the LC_{50} at temperatures range tested. In summary, toxicity of pyrethroid, carbamate, and spinosyn insecticides showed a positive correlation with temperature against *S. littoralis*.

Conclusions

It seems clear from the results that susceptibility of larvae *S. littoralis* against spinosad, lambda-cyhalothrin and methomyl was increased with the increase of temperature. Moreover, these insecticides give good control of resistant strains over a wide range of temperatures and can therefore be incorporated into an integrated strategy to control *S. littoralis*. However, future studies should aim to investigate the mechanism involved in the relationship of temperature to insecticide toxicity and resistance in insects.

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Author contributions
SMI subject selection, study design, carried out the experiments, paper writing, collecting, interpretation of the data, and performing statistical analysis. The author read and approved the final manuscript.

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The data sets used and/or analyzed during the current study are available from the corresponding author on request.

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The authors declare that they have no competing interests.

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