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Susceptibilities of Indian Meal Moth and Almond Moth to Eight *Bacillus thuringiensis* Isolates (Lepidoptera: Pyralidae)^{1,2}

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ABSTRACT: Concentration-mortality curves were determined for 8 *Bacillus thuringiensis* isolates against 3 Indian meal moth and 3 almond moth populations. Relative toxicities of the isolates were not consistent among species or populations of each species, which indicates that general broad conclusions about the nature and effectiveness of *B. thuringiensis* cannot be drawn without considering insect population variation, bacterial isolate differences, and their interactions.

Bacillus thuringiensis Berliner is a potential control agent for the Indian meal moth, *Plodia interpunctella* (Hübner), and the almond moth, *Ephesia cautella* (Walker), both cosmopolitan pests of stored grain and grain products (McGaughey, 1975, 1976, 1978; Kinsinger and McGaughey, 1976). However, populations of both of these moths differed widely enough in their responses to Dipel®, a commercial formulation of *B. thuringiensis* subsp. *kurstaki*, that a wide range of application rates might be required to obtain effective moth control (Kinsinger and McGaughey, 1979). McGaughey and Dicke (unpublished data) found that more than 300 isolates of *B. thuringiensis* had a wide range of efficacy against a laboratory colony of each of these moth species. We attempted to determine if different populations of Indian meal moth and almond moth would exhibit consistent responses to several *B. thuringiensis* isolates. We determined concentration-mortality curves for the response of each population to each isolate and compared susceptibilities.

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² Mention of a proprietary product does not constitute an endorsement by the USDA.

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Table 1. Origin of Indian meal moth and almond moth populations and code designations assigned to each.

Code designation	Obtained from . . . ^a	Origin	Date of colonization
<i>Indian Meal Moth</i>			
BNB-L-IMM	1	Beatrice, NB	1968
MKS-L-IMM	1	Fresno, CA	before 1972 ^b
PMO-W-IMM	2	Pattonsburg, MO	June, 1975
<i>Almond Moth</i>			
FCA-L-AM	3	Riverside, CA	before 1967 ^b
MKS-L-AM	1	Manhattan, KS	before 1974 ^b
SGA-L-AM	4	Unknown	before 1970 ^b

^a 1 = U.S. Grain Marketing Research Laboratory, Manhattan, KS. 2 = Place of origin. 3 = Stored-Product Insects Research Laboratory, Fresno, CA. 4 = Stored-Product Insects Research and Development Laboratory, Savannah, GA.

^b Exact date unknown.

Materials and Methods

Three populations each of the Indian meal moth and the almond moth that were representative of the range in responses to Dipel in a previous study (Kinsinger and McGaughey, 1979) were selected. The moth populations were obtained in 1975 from various locations (Table 1) and were maintained on a ground-wheat larval diet fortified with glycerol, honey, yeast, and wheat germ. Seven *B. thuringiensis* isolates belonging to 5 serotypes (Table 2) were selected as representatives of the more effective of the 300 isolates studied previously (McGaughey and Dicke, unpublished data). The isolates and Dipel were assayed against each of the moth populations.

The experimental *B. thuringiensis* formulations were prepared by H. T. Dulmage, Cotton Insects Research Laboratory, Agricultural Research, Science and Education Administration, USDA, Brownsville, TX. They were produced by submerged fermentation in medium B-4, a Proflo[®]-based substrate, in shake flasks following procedures described by Dulmage (1971). Dry formulations were obtained from fermentation beers by coprecipitation with lactose using acetone (Dulmage et al., 1970). The final preparation consisted of the spore- δ -endotoxin complex, lactose, and insoluble fermentation residues. Formulations were designated by HD-number (isolate number in Dulmage's culture collection) followed by an R-number designating the fermentation run in which the material was produced.

The formulation of each isolate was suspended in water at a rate calculated to produce the highest concentration desired. Serial 1:2 dilutions were then made to produce 8 concentrations of the formulations. Dose ranges for

Table 2. *Bacillus thuringiensis* isolates with serotype, fermentation run, and subspecies tested against populations of Indian meal moth and almond moth.

Isolate	Fermentation run	Serotype	Subspecies
HD-87	R651B	3a, b	<i>kurstaki</i>
HD-128	R668C	7	<i>aizawai</i>
HD-232	R639C	5a, b	<i>galleriae</i>
HD-282	R723B	7	<i>aizawai</i>
HD-283	R711C	7	<i>aizawai</i>
HD-288	R679A	1	<i>thuringiensis</i>
HD-301	R715B	9	<i>tolworthi</i>
Dipel®		3a, b	<i>kurstaki</i>

each isolate were estimated from the results of earlier studies. The suspensions were applied to the ground-wheat larval diet at a rate of 8 ml/80 g and were mixed in bowls using an electrically driven, three-blade polyethylene stirrer. A water-treated check was used. The 80-g samples were divided into 3 replications of ca. 27 g each and placed in glass jars with filter-paper covers. Fifty eggs were added to each jar. The jars were held at $25^{\circ} \pm 1^{\circ}\text{C}$ and 60% RH until the adults emerged. This procedure was repeated for each population. Egg hatchability, monitored each time, was always $\geq 95\%$.

Mortality percentages were calculated from the difference between the number of eggs added and adults that emerged. Values were corrected for mortality in untreated samples and the corrected mortality values then were used to calculate concentration-mortality curves for each replicate by probit analysis. Median lethal concentrations (LC_{50} values) and slopes of the con-

Table 3. Median lethal concentrations (LC_{50} values) for populations of Indian meal moth on a ground-wheat diet treated with indicated *B. thuringiensis* isolates.

<i>B. thuringiensis</i> isolate	LC_{50} (mg/kg) for population ^a			Overall isolate mean
	PMO-W-IMM	BNB-L-IMM	MKS-L-IMM	
HD-301	A 3.60a	B 12.56a	C 19.04a	11.77
HD-87	A 7.45ab	B 18.97b	B 20.76a	15.73
HD-283	A 9.69ab	B 20.99bc	B 21.10a	17.26
HD-288	A 12.21 ^b	C 33.22d	B 22.37a	23.90
HD-282	A 7.19ab	B 22.15bc	C 29.71b	19.68
HD-232	A 8.59ab	B 37.68d	B 32.75b	26.34
HD-128	A 10.22b	B 25.71c	C 35.48b	23.81
Dipel	A 9.68ab	B 35.80d	B 34.11b	26.53

^a Mean of 3 replications; means within each row not preceded by the same letter differ significantly as do means within each column not followed by the same letter, 5% level, LSD test.

^b Mean of only 2 replications.

Table 4. Median lethal concentrations (LC_{50} values) for populations of almond moth on a ground-wheat diet treated with indicated *B. thuringiensis* isolates.

<i>B. thuringiensis</i> isolate	LC_{50} (mg/kg) for population ^a			Overall isolate mean
	MKS-L-AM	FCA-L-AM	SGA-L-AM	
HD-232	A 1.31a	A 19.59a	A 15.81a	12.24
HD-87	A 6.63ab	A 22.30a	A 33.09a	20.67
HD-301	A 8.13ab	A 31.76a	A 35.05a	24.98
HD-288	A 5.23ab	BA 35.11a	B 47.17a	29.17
Dipel	A 10.68ab	B 45.01a	C 81.89b	45.86
HD-283	A 27.91ab	B 104.80b	B 97.74b	76.82
HD-282	A 39.08 ^b	B 106.94b	C 293.72 ^b c	140.92
HD-128	A 91.46c	B 241.42c	C 433.28d	255.38

^a Means of 3 replications; means within each row not preceded by the same letter differ significantly as do means within each column not followed by the same letter, 5% level, LSD test.

^b Mean of only 2 replications.

concentration-mortality curves were then compared by analysis of variance, and means were separated by the LSD procedure. The LC_{50} was chosen for comparisons because variation is less about that point on the concentration-mortality curves than at any other point.

Results and Discussion

Analysis of the data showed significant interactions between the moth population susceptibility and *B. thuringiensis* isolate potency for both moth species. But, the interactions were significant only for the LC_{50} values, not for the slopes of the concentration-mortality curves. The interactions apparently resulted from inconsistencies in the order and relative levels of population susceptibility and isolate potency.

The LC_{50} values for the Indian meal moth populations are summarized in Table 3. Comparisons were made between mean LC_{50} values of the populations within each isolate, and of the isolates within each population. In all comparisons of populations within each isolate, PMO-W-IMM was significantly ($P < 0.05$) more susceptible than the other 2. There were some inconsistencies, however, in the relative responses of BNB-L-IMM and MKS-L-IMM. With isolates HD-87, HD-232, HD-283, and Dipel, responses of the 2 populations did not differ significantly ($P \geq 0.05$). However, with isolates HD-128, HD-282, and HD-301, BNB-L-IMM was more susceptible than MKS-L-IMM, and with isolate HD-288, BNB-L-IMM was less susceptible than MKS-L-IMM. Relative potencies of the isolates to the different populations also were inconsistent. Few differences between means were found

within the most susceptible population, PMO-W-IMM. However, several differences could be detected in potencies within the less susceptible populations, BNB-L-IMM and MKS-L-IMM.

Similar comparisons between mean LC_{50} values for the 3 almond moth populations (Table 4) showed no differences in responses to HD-87, HD-232, and HD-301. MKS-L-AM, in general, was more susceptible than the other 2 to the remaining isolates. Responses of the other 2 populations to HD-283 or HD-288 did not differ. However, FCA-L-AM was more susceptible than SGA-L-AM to HD-128, HD-282, and Dipel. As with the Indian meal moth, almond moth population responses to the various isolates differed less within the most susceptible population than within the less susceptible populations. There were a few changes in the order of potency of the isolates from one population to another, but, the isolates' rankings generally were more consistent among almond moth populations than among Indian meal moth populations.

Differences between mean responses of the 2 moth species to different isolates were not examined statistically because of the large heterogeneity of variance between the 2 species. Also, these populations were studied because they represent a wide range in susceptibility to *B. thuringiensis* (Kinsinger and McGaughey, 1979) rather than being typical of the species. The isolate \times population interactions found within each species are apparent when the responses of the 2 species are compared. Indian meal moth populations were generally more susceptible than almond moths, ranking 1st, 2nd, 3rd, or 4th in susceptibility while almond moth populations tended to rank 4th, 5th, or 6th. However, isolate HD-232 was more toxic to almond moths, with the 3 populations ranking 1st, 3rd, and 4th in susceptibility and Indian meal moth populations ranking 2nd, 5th, and 6th. Also, the most susceptible almond moth population, MKS-L-AM, ranked 1st or 2nd in susceptibility to 5 isolates. Thus, for most of the isolates, relative toxicity to these 2 species depends upon the populations used for testing, and the other isolates would probably yield similarly confusing data if tested against additional populations of these species.

These data confirm earlier findings that *B. thuringiensis* isolates differ in potency, that Indian meal moth and almond moth differ in susceptibility, and that populations of these species also differ in susceptibility. However, the interactions between population susceptibility and isolate potency found here indicate that caution must be exercised when attempting to categorize *B. thuringiensis* isolates on the basis of their potency to different insect species. The biochemical nature and mode of action of *B. thuringiensis* must be more thoroughly explored before the cause and significance of these interactions can be fully understood.

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