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관개방제의 효력예측을 위한 시뮬레이션

Simulation of Chemigation Efficacy

구영모* 해롤드 썸너** 래리 챈들러**
정회원
Y.M. Koo H.R. Sumner L.D. Chandler

적 요

관개방제 기술의 변수 및 효력예측을 위한 컴퓨터 시뮬레이션 프로그램이 油化/散化液滴의 부착율, 유충의 推計的 亂步운동 및 無作爲 농약흡수 이론을 이용하여 개발되었다. 시뮬레이션 결과는 밤나방 유충, Spodaptera frugiperda (J.E. Smith) (Lepidoptera : Noctuidae)을 이용한 방제효력 실험결과와 비교하였다. 이론치와 실험치는 서로 일치되었다. 방제율은 농약유효성분량이 증가함에 따라 증가하였으며 크로포(chlorpyrifos) 약제의 표준 권고량인 670g〔AI〕/ha에서 완전방제가 예상되었다. 油化액적(emulsion)은 상대적으로 직경이 큰 散化액적(dispersion) 보다 작물잎표면에 부착이 어려워 낮은 방제율을 나타내었다. 액적직경이 방제효력에 미치는 영향은 목화작물에 대하여 낮은 약제량에서 뚜렷하게 나타났고, 그 영향은 약제량이 증가할 수록 목화 및 옥수수 모두에서 저하되었다. 葉形係數는 작물의 엽상구조에 따른 액적의 부착 및 계류에 미치는 영향을 의미한다. 고찰된 관계방제기술의 영향요소에 대한 이해는 농약사용의 감소 및 효력의 증가에 중요한 역할을 한다.

주요 용어(Key Words) : 관개방제 (Chemigation), 방제효력 (Efficacy), 액적직경 (droplet diameter), 밤나방 (Fall armyworm), 크로포 (Chlorpyrifos).

1. Introduction

Koo et al. (1992c) evaluated the effects of I/O (Insecticide-oil)[1] droplet size, active chemical rate, and crop canopy architecture on percent larval control by chemigation. A mixture of chlorpyrifos and immiscible oil was applied through a laboratory chemigation system onto corn and cotton plants that contained fall armyworm (FAW) larvae. I/O emulsions affected larval control less than I/O dispersions due primarily to a lower deposition efficiency of emulsions. Percent larval control on corn plants was higher than on cotton plants because of the effect of canopy architecture. Insecticide deposition during chemigation was measured by Wauchope et al. (1991). Results showed that a mixture of chlorpyrifos and soybean oil initially retained three times more chlorpyrifos on corn foliage than did an emulsion formulation.

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* Dept. of Agricultural Machinery, Kyungpook National University, Taegu, Korea.

** USDA-ARS, IBPMRL, Tifton, GA, USA.

[1] A mixture of insecticide concentrate and immiscible oil.

Shaw (1980) stated that smaller oil droplets were more hydrophilic than larger droplets in a poly-dispersed system. Therefore, the smaller droplets tended to dissolve, while the larger droplets adhered to a surface or coalesced together. An increase in droplet diameter results in an energy increase at the droplet surface. The interfacial free energy can be expressed in the form of $\gamma_{o/w}\pi D^2$ where D is the diameter of a droplet and $\gamma_{o/w}$ is the interfacial tension between the dispersed phase and the continuous phase (Sharma and Shah, 1985). Ruckenstein and Chi (1975) pointed out that a stable emulsion formed when the specific free energy was sufficiently small. Their results implied that the interfacial free energy affected the affinity of an individual droplet.

Some studies have evaluated the influence of droplet diameter, number density of droplets, chemical concentration, and crop canopy architecture on the effectiveness of insecticides against insect pests (Wofford et al., 1987 ; Adams et al., 1988). A simulation model estimating insecticide uptake has been investigated using Egyptian cotton leafworm (ECLW) larvae, *Spodoptera littoralis* (Salt and Ford, 1984). The computer model was useful to understand the kinetics of larvae-chemical interaction as well as the quantitative prediction of larval control.

The objectives of this study were : (1) to simulate percent larval control with a computer model using theories of droplet deposition, larval movement and chemical uptake. (2) to compare the simulation results with experimental percent control against fall armyworm larvae, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera : Noctuidae), and (3) to develop ways to improve chemigation efficiency by understanding factors that influence percent larval control.

2. Materials and Methods

A. Experimental Methods

An experiment was designed to verify a theoretical efficacy model. Test variables of the chemigation experiment were the crop type (corn and cotton), active chemical rate (0.0, 83.4, 166.9 and 333.8 g[AI]/ha), and I/O droplet size (emulsion and dispersion). Dursban®6(chlorpyrifos, 719g[AI]/l[Formulation] : DowElanco) was blended with Sunspray® 11N oil (Sun Refining and Marketing Co.) for injection into a laboratory chemigation system. A factorial experiment was designed for each test set using two replications. Three test sets of the same experimental design were conducted.

1) Generation of Insecticide-oil Droplets

A mixture of chlorpyrifos and oil was injected into a laboratory chemigation system at 1.0 ml/min with an FMI metering pump through a 1.6 mm I.D. injection port. The I/O droplets in the water line were dispersed through two swirl chamber nozzles (WhirlJet^R 1/4 B5-5W, Spraying System Co.) at a pressure of 345 kPa. A total flow rate in the laboratory chemigation system was 14.0 l/min. Accordingly, the nozzle discharge and by-pass flow rates were 7.0 l/min. An average flow velocity in the swirl chamber nozzles was estimated to be 7.4 m/s with an average inlet area of 7.9 mm^2 in the swirl chamber. Dispersion and emulsion characteristics of oil droplets during chemigation were investigated by Koo et al. (1992a, 1992b). These studies concluded that droplet diameters of immiscible oil (the dispersed phase) could be predicted by estimating the average flow velocity of water (the continuous phase). Therefore, droplet size distribution was predicted from the average velocity of the continuous phase.

A mechanical homogenizer, Stellar-flo^R (Cherry-Burrell Corp.), was used with a high pressure piston pump to mechanically emulsify a mixture of chlorpyrifos and oil. The liquids were metered into the homogenizer at 99.0 ml/min of water and 1.0 ml/min of the I/O mixture. The emulsions of the mixture created in the homogenizer were injected into the chemigation system at a rate of 100 ml/min through the same injection port. The emulsion was discharged under the same conditions. Droplet size distributions of the dispersion and emulsion were presented in Table 1.

2) Chemigation Procedure

Host plants selected for the tests were corn (Sunbelt^R 1803) and cotton (McNair^R 235) which represented canopy architecture characteristics of mono- and dicotyledon species. The host plants were seeded in a bedding container (54 cm x 28 cm) that held eighteen 9-cm square pots (3 rows of 6 pots). Fifteen days after planting, an average of 8.0 one-day old FAW larvae (first instar) per plant were artificially introduced on cotton plants (5 to 6 leaf stage). The following day, an average of 2.5 one-day old FAW larvae per plant were placed on corn plants (4 to 5 leaf stage). The larvae were manually introduced using a larval dispenser that delivered a uniform number of larvae per plant in corncob grits (Wiseman et al., 1980). The larvae were allowed 3 (corn) and 4 days (cotton) to establish on the plants before chemigation treatment.

A water flow network and plant conveyor system was constructed for laboratory chemigation research (Koo et al., 1992c). All insecticide treatments were applied using the laboratory chemigation system. Each treatment was applied to potted plants in two bedding containers holding 36 pots arranged in 3 rows of 12 pots. Treatments were delivered in the designated test area, 108 cm wide x 28 cm long. The average irrigation rate was 3.3 mm (30.5 kl/ha) over a swath of 107 cm at a conveyor speed of 2.14 m/min. The inert oil application rate was 2.1 l/ha. Three days after treatments were applied the number of plants and live larvae were counted for each treatment. Percent larval control of FAW were calculated from the results of these counts. The natural mortality, mortality[2] of larvae in the check, varied among test sets due to biological, environmental and experimental variations. Therefore, the percent larval control (CNTRL) was used to normalize the variation in natural mortality among test sets

Table 1. Insecticide-oil droplet size distrbutions* used for verifying the computer model of a theoretical efficacy.

Type	$D_{v.1}$	$D_{v.5}$	$D_{v.9}$	Volume fraction(%)				$D_{N.1}$	$D_{N.5}$	$D_{N.9}$	Number fraction(%)			
		(μm)		<5μm	5-20	20-100	>100		(μm)		<5μm	5-20	20-100	>100
Dispersion	31.3	74.1	196.5	0.0	0.8	62.1	37.1	3.6	14.2	40.7	22.3	32.4	44.7	0.6
Emulsion	1.8	5.9	26.3	40.0	46.7	13.3	0.0	0.4**	1.4	3.0	96.4	3.6	0.0	0.0

* The distributions are predicted from regression equations (Koo et al., 1992b).

* * extrapolated using $D_{N.5}$ and $D_{N.9}$(ASAE Standards, 1995)

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2) Mortality(MOT)is defined as

$$MOT(\%) = \left[1 - \frac{\#\text{ of live larvae}}{\#\text{ of infested larvae}}\right] \times 100$$

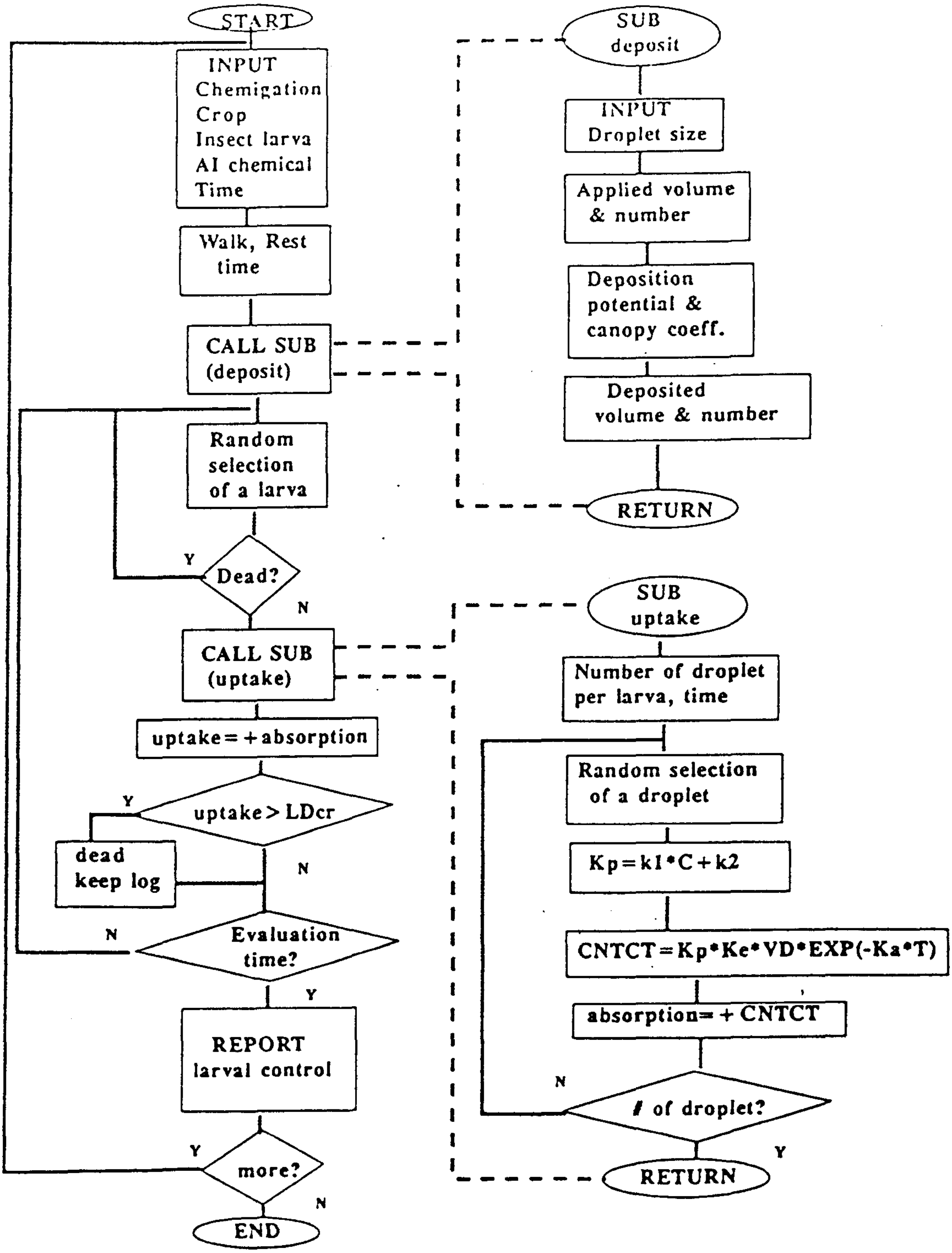

Fig 1. Schematic flow diagram of the computer program simulating the efficacy of insecticide-oil droplets applied through chemigation.

Table 2. Input parameters and values used for the simulation of percent larval control(Koo et al., 1992 c ; Salt and Ford, 1984 ; Wauchope et al., 1991).

Category	Parameter	Value	Unit
Chemigation	Oil carrier	11N	
	Injection rate	1.0	ml/min
	Irrigation rate	30.5	kl/ha
	swath width	108	cm/min
	speed	214	cm/min
	I/O rate	2.1	l/ha
	AI rate	83.4 166.8 333.6	g/ha
	Evaluation area	3024	cm^2
Insecticide/oil droplets	Size distributions	Infile	
	Dispersing type	Emulsion, Dispersion	
	Degradation coff.(Ka)	.0004(E), .0006(D)	
	D_{ref}	322.8	μm
Chemical compound	Common name	Chlorpyrifos	
	Commercial name	Dursban 6(719g AI/1)	
	Concentration(v/v)	.0528, .1056, .2112	
	LD50(FAW larva)	.008	mg/g
Crop canopy	Host plant	Corn, Cotton	
	Number of plant	36	
	Canopy coeff.(Kc)	1.1(Corn) 0.99(Cotton)	
Insect larval characteristics	Body weight	.001	g
	width	.1	cm
	Infestation rate	2.0	#/plant
	Walk speed	23.0	cm/min
	Ratio pad/body areas	.13	
	Transition prob. RR	.85	
	(R : resting state) WR	.195	
	(W : walking state) RW	.15	
	WW	.805	
	Absorption K_1, K_2	0.2, 0.0739	
Iteration time	Increment	1.0	min
	Evaluation(3 days)	4330	min
Program determined parameters	Critical uptake(LDcr)	8.0e-6	mg/larva
	Evaluation ratio(Ke)	.06542	
	Trail area	2.3	cm^2/min
	Footing area	.299	cm^2/min
	Ratio foot/eval.areas	9.89e-5	
	Time in WW state	4.128	min
	Time in RR state	5.667	min
	Total walking time	1820	min
	Total resting time	2500	min

using Equation (1).

$$\mathrm{CNTRL}(\%) = \frac{\mathrm{MOT}-\mathrm{MOT}-\mathrm{CHK}}{100-\mathrm{MOT}-\mathrm{CHK}} \quad \cdots(1)$$

where MOT – CHK is the average natural mortality of each test set. After the normalization of data, the two replications of three test sets were concatenated into 6 replications.

B. Computational Methods

A simulation program was written in BASIC^R to predict percent larval controls for chemigation treatments. A flow chart of the program is presented in Figure 1. Input parameters were initialized before a program execution by obtaining values from a data file and terminal entries. The values of the parameters are identified in Table 2. The categories of the input parameters were the chemigation condition, droplet size distribution, chemical compound, crop canopy type, larval characteristics and iteration time. The deposition of I/O droplets on the foliage was estimated using the canopy coefficient, deposition potential and droplet size distribution. The available droplets in the test area are subjected to random encounters with selected larvae. Larval selection was accomplished using an unpredictable random function. The size of droplet likely to be encountered was also selected randomly ; however, the frequency of the selection depended on the number distribution of droplets deposited on the foliage. The time spent in a behavioral states of larvae was expressed using a stochastic process. The larval encounter with I/O droplets was repeated for the number of droplets that were available for a larva per unit time.

Chemical uptake during an encounter was absorbed and accumulated to a pre-existing chemical in a larva. When the accumulative amount of active chemical was more than a critical lethal uptake (LDcr), the larva was logged dead. The random selection of a larva and droplets continued until reaching a designated evaluation time or 100 % larval control. The six simulations (replications) were conducted for a treatment using the same experimental conditions. The execution time and order of simulations were also randomly selected to accomplish a complete random process.

1) Deposition of Droplets

The simulation program obtained volume and number distributions of I/O droplets applied through chemigation, and determined the distributions of droplets deposited on the foliage using the relative free surface energy of a droplet. The volume and number percents in each size class were determined, and number of droplets in each size class was determined as if 0.95 ml of I/O mixture were dispersed. The interfacial free energy is a function of the surface area of a droplet (πD^2). The deposition potential of droplets in a size class was estimated using the relative surface area to a reference surface area of a droplet ($D_{ref}=322.8\mu m$). The number and volume of droplets in a size class were multiplied by the deposition potential to estimate the number and volume of I/O droplets deposited on foliage (Sharma and Shah, 1985 ; Ruckenstein and Chi, 1975).

The number of retained droplets depends on the crop canopy architecture as well as the deposition potential. I/O droplets on corn plants are collected into corn whorls where larvae exist ; however, droplets on cotton plants are drifted from flat-flap leaves. This simulation program adjusted the retention characteristics of droplets on the crop canopy by a constant of the canopy coefficient (Kc). The evaluation ratio (Ke) was determined using the chemigation speed, spray swath width, I/O injection rate and the evaluation area to estimate available volume for a larva per unit time. In the calculation process, both of the ± 2.5 % tails in the droplet size distributions were discarded to avoid round-up error.

2) Larval Movement

A larva spends its time on the treated foliage surface in one of three behavioral states : resting (R), feeding (F), or walking (W). The larval behavior on the foliage can be expressed with stochastic transition probabilities. Salt and Ford (1984) found that the presence of active chemical inhibited feeding activity of ECLW larvae, *Spodoptera littoralis.* The FAW larvae, *Spodoptera frugiperda,* used in the experiment was from the same genera ; therefore, the behavior of FAW larvae on treated surfaces was assumed as a two-state Markov chain. The Markov chain with two states (R and W) is modelled in Equation (2).

$$P = \begin{vmatrix} R_{RR} & P_{RW} \\ P_{WR} & P_{WW} \end{vmatrix} \qquad \cdots\cdots(2)$$

where P is the transition matrix and P_{IJ} are the probability elements. The average number of time spent in state I, before a transition to another state J is P_{II}/P_{IJ} where $P_{II}+P_{IJ}=1$. The probability of contact with I/O droplets was related to walking time during total evaluation time.

Salt and Ford (1984) stated that chemical uptake and absorption took place at the interface of false-leg pads and insecticide droplets. A footing area per a unit time can be estimated from the product of the pad/body area ratio and trail area during movement. The larval walking speed, number of larvae, test area and larval footing area determined the footing area per larva for a unit time. The ratio of the footing area to the test area gave the activity coefficient (Kw). The product of Kw and the number of I/O droplets in the test area resulted in the number of droplets available for a larva per a unit time.

3) Chemical Uptake

Little is known concerning the uptake and accumulation of insecticide in the insect larval body after contact with spray droplets containing active chemical. Larval encounter with I/O droplets was assumed to be a random occurrence. An unpredictable random function was used to simulate encounter events. The number of contacts for a random occurrence was estimated from the evaluation ratio (Ke) and the activity coefficient (Kw).

The absorption of active chemicals into an insect larval body has a pharmacokinetic relationship with the applied dose (Salt and Ford, 1984). The absorption coefficient (Kp) may have a linear relationship with the chemical concentration, thus $Kp = k_1 C + k_2$, where C is the AI concentration in a mixture and k_1 and k_2 are constants. The applied chemical degrades over time (Wauchope et al. 1991). The persistence of emulsion or dispersion follows a negative exponential curve, $EXP(-K_a t)$, where Ka is the degradation coefficient and t is time in minute. For every random encounter with a droplet, a randomly selected larva accumulated a certain amount of AI chemical, defined in Equation (3).

$$CNTCT = K_p \times K_e \times VD \times EXP(-K_a t) \cdots (3)$$

where CNTCT is the amount of AI absorbed during an encounter, and VD is the volume in a size class containing a randomly selected droplet.

3. Results and Discussion

Figures 2 and 3 present the (a) simulated and (b) experimental FAW larval controls as influenced by the active chemical rate for the dispersion and emulsion applied via chemigation on corn and cotton, respectively. The agreement of simulation and experimental results was analyzed for each treatment using t-tests. T-test results indicated that simulations agreed with experimental results (Table 3). These results revealed that overall trends and sensitivities of major variables on larval control could be predicted with the simulation program.

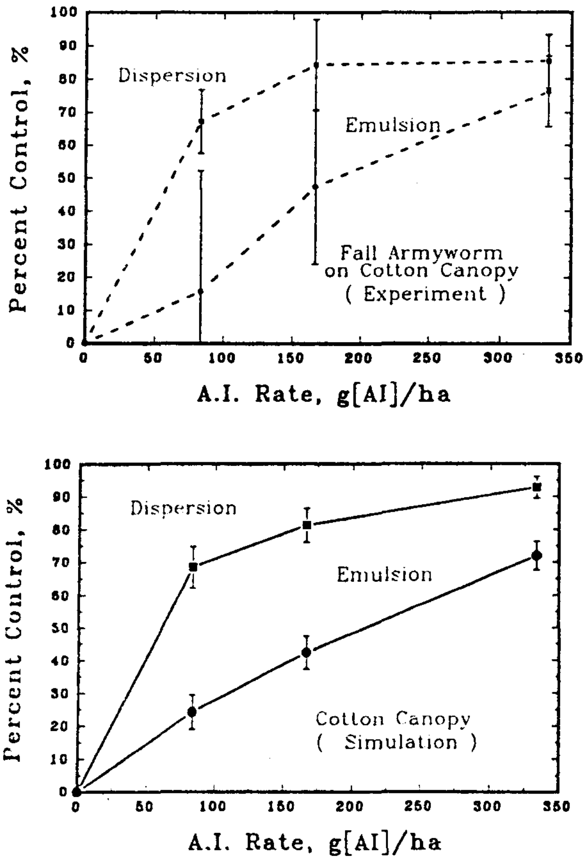

Fig 2. Simulation (a) and experiment (b) results of percent larval control on corn canopy as influenced by active chemical rates for emulsion and dispersion. Vertical bars represent one standard deviation.

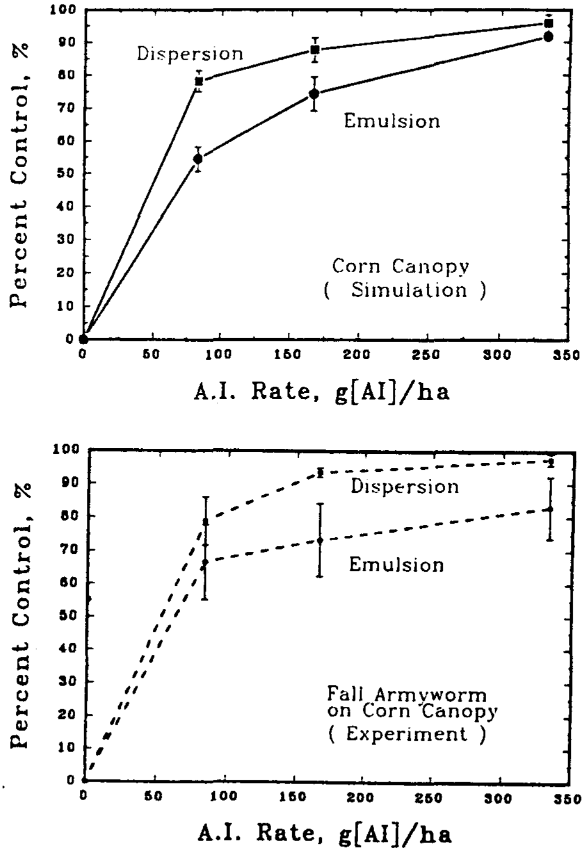

Fig 3. Simulation (a) and experiment (b) results of percent larval control on cotton canopy as influenced by active chemical rates for emulsion and dispersion. Vertical bars represent one standard deviation.

ANOVA conducted for simulation and experimental data indicated that the active chemical rate and I/O droplet size were the major variables affecting the percent larval control in both corn and cotton. Interactions of the variables were greater in the simulation than in the experiment. Replication was not significant in either

Table 3. Comparions of simulation means with experimenatal data for percent larval control using t-test as influenced by the droplet size and active chemical rate for corn and cotton.

AI rate (g/ha)	Means of % control	Cotton		Corn	
		Dispersion	Emulsion	Dispersion	Emulsion
83.4	Experiment	67.3	15.8	78.8	66.5
	Simulation	68.5	24.3	78.3	54.6
	Prob. 〉| t |	0.7927	0.5849	0.8749	0.0335*
166.8	Experiment	84.4	81.3	93.5	73.3
	Simulation	47.4	42.4	87.7	74.3
	Prob. 〉| t |	0.6082	0.6171	0.005**	0.8461
333.6	Experiment	85.4	76.3	97.5	83.0
	Simulation	92.8	72.0	95.8	91.7
	Prob. 〉| t |	0.0615	0.3811	0.2350	0.0464*

*,** indicate t-test significance at 5% and 1% lebvels, respectively. Probability 〉 | t | is estimated under a hypothesis of equal variance using 6 observations for each treatment.

simulation nor experiment. The standard deviations for experimental data were greater than those of simulation data. Larval control increased with an increase in chemical rate. Complete larval control (100 %) was predicted as the chlorpyrifos dose neared a recommended rate of 670 g[AI]/ha for both crops. The I/O emulsion resulted in lower insecticide efficacy than did the I/O dispersion in both crops (Figures 2 and 3). The influence of droplet size on larval control was more apparent on cotton at lower chemical rates than other conditions in both simulation and experiment. The influence of droplet size on larval control was diminished at a higher chemical rate on both crops in the simulation and experiment. Thus, the greater insect control and insecticide deposition previously observed (Chalfant and Young, 1984 ; Wauchope et al., 1991 ; Koo et al. 1992c) with the I/O dispersions compared with I/O emulsions, were apparently due to the effect of droplet diameter. The emulsions adhered less to the plant surface than did the dispersions, thus lowering larval controls. The number of droplets generated per unit volume of I/O increased with a decrease in droplet size ; however, the number of droplets retained on foliage was limited by the decreasing deposition efficiency. Thus, insecticide uptake by larvae was also limited by the lower number of contacts with the I/O droplets.

The percent control of FAW larvae on corn was higher than that on cotton due to a funnel effect of corn whorls. I/O droplets chemigated on corn were collected into corn whorls (Kc=1.1) where FAW larvae existed, thus exposing the larvae to more I/O droplets. However, the flat-flap cotton (Kc=0.99) leaves retained fewer I/O droplets compared to a perfect flat surface (Kc=1.0), thus resulting in lower larval controls.

The computer simulation and laboratory tests are not directly applicable for determining optimal conditions to manage FAW larvae in the field with chemigation ; however, the results strongly suggest ways by which the efficiency of chemigation operations can be improved. Although the application rate of chlorpyrifos was reduced from 250 to 90 g[AI]/ha, 80% control of FAW larvae was achieved by applying large I/O droplets (dispersion) rather than small I/O droplets (emulsion) on corn (Figure 2). Likewise, a reduction of the active chemical rate from 330 to 150 g〔AI〕/ha maintained 80% larval control on cotton (Figure 3).

Some of the input variables used in the simulation were estimated based on available data from the literature. Caution should be used in applying these results until specific input data are obtained and evaluated in the simulation model.

4. Conclusions

The efficacy of I/O droplets applied through a laboratory chemigation system was simulated using a computer program employing the deposition potential, the stochastic larval movement, and the random chemical uptake occurrence. The simulation result was compared with experimental efficacy of chemigated droplets evaluated against FAW larvae artificially introduced on corn and cotton plants. The simulated and experimental results appeared similar and agreed statistically. The effects of I/O droplet size, active chemical rate, and crop canopy architecture on larval control were predicted and investigated. This simulation confirmed that dispersed I/O droplets applied through a chemigation system achieved greater larval control than did emulsified I/O droplets. Larval control on corn plants was better than that achieved on cotton plants primarily because of the retention characteristics of corn whorl. The greater influence of I/O droplet size on larval control was demonstrated when a lower chemical rate was applied on cotton.

Chemical uptake by larvae was related to the deposition efficiency of I/O droplets on the foliage, the number of larval contacts with I/O droplets, biological response of larvae to chemical, persistence of chemical compound and AI concentration of I/O droplets. The understanding of interactive parameters for controlling insects should significantly advance opportunities to perfect the use of chemigation technology for managing primary insect pest species. Additional work is needed to delineate the deposition and mortality induction processes. The detail of insecticide AI absorption by an insect for each contact with a droplet should be defined through entomological studies. The simulation model and input parameters need to be further developed and estimated.

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