Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252026v3915318rc

Scientific Article

Spray application quality and estimated probability of fall armyworm control in maize

Qualidade da pulverização e probabilidade estimada de controle da lagarta-do-cartucho em milho

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ABSTRACT - Efficient pesticide application supports crop performance while limiting waste, costs, environmental contamination, and human health risks. Unsuitable spray nozzles, application volumes, or pesticide concentrations may increase drift, runoff, ineffective pest control, and phytotoxicity. These losses can contaminate soil and water, harm non-target organisms, and expose agricultural workers to potentially toxic residues. This study evaluated spray application quality and the estimated probability that deposited doses reach or exceed literature-derived LD_{80} reference values for *Spodoptera frugiperda* in maize. The experiment was conducted at the University of Rio Verde (UniRV) during the 2022 and 2023 maize growing seasons, with evaluations at growth stages V4 and V8, respectively. A randomized complete block design with split plots and four replications was adopted. Treatments combined application volumes of 50 and 100 L ha^{-1} with three hydraulic nozzles: flat-fan (XR110015), twin flat-fan (TXA80015), and hollow -cone (AD-02/D). Spray deposition was measured by spectrophotometry, whereas droplet density and spray coverage were assessed using water-sensitive papers. The experimental approach allowed comparison of how spray delivery changed with application volume and nozzle configuration. Based on reference insecticide values reported in the literature, a probit model estimated probabilities of deposited doses reaching or exceeding LD_{80} thresholds. The single flat-fan and hollow-cone nozzles generally produced greater deposition, particularly at 100 L ha^{-1}. These conditions also yielded higher estimated probabilities of reaching LD_{80} reference values for certain insecticide–population combinations. However, neither larval mortality nor plant damage was directly assessed. Consequently, these probabilities are comparative model predictions rather than experimental evidence of effective field control.

Keywords: Spray deposition. Coverage efficiency. Hydraulic spray nozzles. *Spodoptera frugiperda.* Spray volume.

RESUMO - A aplicação eficiente de pesticidas favorece o desempenho das culturas, reduzindo desperdícios, custos, contaminação ambiental e riscos à saúde humana. Pontas de pulverização, volumes de aplicação ou concentrações inadequadas podem aumentar deriva, escorrimento, falhas de controle e fitotoxicidade, contaminando solo e água, afetando organismos não alvo e expondo trabalhadores a resíduos tóxicos. Este estudo avaliou a qualidade da pulverização e a probabilidade estimada de as doses depositadas atingirem ou superarem valores de referência de DL_{80} para *Spodoptera frugiperda* em milho, obtidos na literatura. O experimento foi conduzido na Universidade de Rio Verde (UniRV), nas safras de 2022 e 2023, com avaliações nos estádios V4 e V8, respectivamente. Adotou-se delineamento em blocos casualizados, com parcelas subdivididas e quatro repetições. Os tratamentos combinaram volumes de 50 e 100 L ha^{-1} e três pontas hidráulicas: jato plano simples (XR110015), jato plano duplo (TXA80015) e cone vazio (AD-02/D). A deposição foi quantificada por espectrofotometria; densidade de gotas e cobertura, por papéis hidrossensíveis. O delineamento permitiu comparar deposição entre volumes e pontas. Um modelo probit estimou, com base em valores de referência de inseticidas publicados, as probabilidades de as doses depositadas atingirem ou superarem a DL_{80}. As pontas de jato plano simples e cone vazio geralmente proporcionaram maior deposição, especialmente com 100 L ha^{-1}. Nessas condições, estimaram-se maiores probabilidades de atingir a DL_{80} para algumas combinações de inseticidas e populações. Entretanto, mortalidade larval e danos às plantas não foram avaliados diretamente. Assim, os resultados representam previsões comparativas, não evidências de eficácia do controle em campo.

Palavras-chave: Deposição de calda. Eficiência em cobertura. Pontas hidráulicas de pulverização. *Spodoptera frugiperda.* Volume de calda.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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Received for publication in: March 4, 2026.
Accepted in: October 28, 2026.

Editor in Chief: Aurélio Paes Barros Júnior
Section Editor: Daniel Valadão Silva

Data Availability: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author.

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INTRODUCTION

Maize (Zea mays L.) is one of the most important crops worldwide (ERENSTEIN et al., 2022). According to Duarte, Mattoso and Garcia (2017), it plays a strategic role in both human and animal nutrition and serves as a raw material for several industrial sectors, including ethanol, starch, oil, and bioplastics production. Currently, maize is the second most important agricultural crop in Brazil, with an estimated production of approximately 125 million tons for the 2024/2025 season, cultivated over about 21.3 million hectares (CONAB, 2023).

In this context, between 1986 and 2017, maize production in Brazil increased by 146.87%, while the cultivated area expanded by only 14.36%. This disparity highlights production intensification resulting from the adoption of higher-yielding cultivars, the consolidation of the second crop season, and improvements in crop management and phytosanitary control. These advances enabled productivity gains without the need for significant expansion of cultivated

land (DUARTE; MATTOSO; GARCIA, 2017).

Despite these advances, maize production still faces significant phytosanitary challenges. The fall armyworm (*Spodoptera frugiperda*) is considered the primary pest of maize in Brazil due to its ability to attack plants at different developmental stages, from seedlings to grain formation (SILVA et al., 2020). One of its most distinctive characteristics is its habit of sheltering within the plant whorl, where it feeds on inner leaves, making control difficult and increasing its damage potential (WORDELL FILHO et al., 2016).

Infestation can have severe consequences. Yield losses may reach up to 60%, depending on plant genotype, crop growth stage at the time of attack, and planting season. This scenario reinforces the need for efficient management strategies to reduce pest impacts (PAREDES-SÁNCHEZ et al., 2021).

Among these strategies, adequate deposition of the active ingredient is critical to ensure that pesticides reach the target at sufficient levels to produce the desired effect. Without proper deposition, even effective products may perform poorly in pest control (WANG et al., 2019). Insufficient deposition reduces control efficacy, leaving part of the pest population unmanaged and increasing production losses (XIAO et al., 2020). Conversely, excessive deposition may lead to product waste and increase the risk of negative environmental impacts (ONWONA-KWAKYE; HOGARH; VAN DEN BRINK, 2020).

Another relevant aspect is that exposure of pests to sublethal doses or frequent insecticide applications exerts strong selection pressure, allowing the survival of individuals with favorable genetic traits. This process leads to the gradual development of resistance (FREEMAN et al., 2021), reducing insecticide effectiveness in population control (GAO et al., 2022). Furthermore, excessive reductions in application rates may compromise target coverage, leaving untreated areas that favor pest survival and population resurgence (CONTIERO; BIFFE; CATAPAN, 2018).

Given this scenario, understanding how spray application conditions affect deposition within the maize whorl is essential. Therefore, this study aimed to evaluate spray application quality as affected by nozzle type and spray volume and to relate the experimentally determined spray deposition to the estimated probability of reaching or exceeding literature-derived LD_{80} reference values for Spodoptera frugiperda, considering simulated spray-solution concentrations.

MATERIALS AND METHODS

Experimental conditions

The experiment was conducted in the experimental area of the University of Rio Verde (UniRV) and in a laboratory, both located in the municipality of Rio Verde, Goiás, Brazil, during the 2022 and 2023 maize growing seasons. The soil is classified as a dystroferric Red Latosol (*Latossolo Vermelho Distroférrico*) (SANTOS et al., 2018), and the area has been managed under a no-tillage system. The geographic coordinates of the site are 17°47'06.49" S latitude and 50°57'38.76" W longitude, at an altitude of 765 m.

The experiment was conducted using a randomized complete block design arranged in a split-plot scheme with four replications. Spray volumes of 50 and 100 L ha^{-1} were assigned to the main plots and were obtained using operating speeds of 13.6 and 6.8 km h^{-1}, respectively. Three hydraulic spray nozzles were assigned to the subplots: single flat-fan (XR110015), twin flat-fan (TXA80015), and hollow-cone (AD-02/D). The nozzle treatments were evaluated based on spray coverage, droplet density, and tracer-derived spray deposition.

The maize hybrid P3858PWU (Pioneer®) was sown on April 15, 2022, and April 18, 2023, for the first and second growing seasons, respectively. The final plant density was 3.5 plants m^{-1}, with a row spacing of 0.50 m. Each experimental plot measured 10 m in length and 6 m in width and comprised 12 maize rows.

The study was conducted over two maize growing seasons. In 2022, spray application quality was evaluated at the V4 growth stage, characterized by four fully expanded leaves. In 2023, the evaluation was performed at the V8 growth stage, characterized by eight fully expanded leaves. These growth stages were selected because fall armyworm larvae commonly remain within the maize whorl during vegetative development, where the protected plant architecture may restrict spray penetration and reduce target exposure.

Spray application

Applications were performed using a Condor AM112 ground sprayer (Jacto) with a 600 L tank capacity, coupled to an Agrale 5050 tractor equipped with front-wheel assist.

To install the evaluated spray nozzles, four units of each nozzle type were mounted sequentially along the spray boom, spaced 0.5 m apart, with the operating pressure set at 40 pounds per square inch (psi). The application was performed at a distance of 50 cm from the target.

A tracer dye (Brilliant Blue FDC 1) was added to the spray solution at a concentration of 3,000 mg L^{-1} to quantify spray deposition. Mineral oil (Assist® EC) was also added at 0.25% (v/v) to simulate real field conditions for insecticide applications used in fall armyworm control.

Applications were conducted under suitable environmental conditions, with an air temperature below 30 °C, relative humidity above 55%, and a mean wind speed between 3 and 10 km h^{-1}. Meteorological variables were measured using a portable thermo-hygro-anemometer (Kestrel® 3000) positioned 0.5 m above the crop canopy.

Assessment of spray coverage and droplet density

To evaluate droplet density and spray coverage, four water-sensitive papers (WSPAPER®, 13 × 38 mm) (Figure 1) were positioned inside the whorls of randomly selected maize plants within the central sampling area of each subplot, corresponding to the area reached by the central spray nozzles. After application, the papers were carefully removed, placed between sheets of absorbent paper, and stored in opaque containers to prevent light exposure and preserve droplet-stain integrity until image analysis. The subplot receiving each combination of spray volume and nozzle type was considered the experimental unit, whereas the four water-sensitive papers collected within each subplot were considered subsamples.



Figure 1. Water-sensitive paper positioned inside the maize whorl.

Determination of droplet density and coverage percentage

After application and removal, the water-sensitive papers were digitized using an Epson WorkForce DS-1630 scanner at a resolution of 600 dpi. The resulting images were subsequently analyzed using Gotas® software, following the methodology described by Chaim et al. (2002). From this analysis, droplet density (droplets cm^{-2}) and coverage percentage (%) were determined.

For the analysis of variance, the mean value obtained from the four water-sensitive-paper subsamples was calculated for each subplot. For the regression analyses, the individual values obtained from the subsamples were used to represent the variability in spray coverage and droplet density among the targets sampled within each application condition. These subsamples were used as observational records in the regression models and were not considered additional field replications.

Determination of tracer-derived spray deposition

After spray application, five maize whorls located near the positions where the water-sensitive papers had been placed were collected, placed in plastic bags, and stored at 5.0 °C until laboratory analysis. The whorls were then washed with 30 mL of distilled water inside each plastic bag to extract the tracer dye (Figure 2A). The resulting wash solution was transferred into plastic cups, one per whorl. The solutions were subsequently analyzed using a spectrophotometer (Figure 2B) set to measure absorbance at a wavelength of 630 nm (PALLADINI, 2005). For each sample, a 4 mL aliquot was withdrawn with a syringe and transferred to a glass cuvette for reading.

After washing, the leaf area of the whorls (Figure 3) was measured using ImageJ leaf area analysis. A reference object (ruler) was placed beside the whorl leaf to calibrate the scale, allowing pixel measurements to be converted into real units (cm^2).

The five maize whorls collected within each subplot were considered subsamples of the corresponding experimental unit. For the analysis of variance, the mean deposition value obtained from the five whorls was calculated for each subplot. For the regression models used to estimate the probability of reaching or exceeding the LD_{80} reference value, the individual deposition values obtained from the sampled whorls were retained to represent the variability in spray deposition among targets exposed to the same application condition. These individual measurements were treated as subsample observations and not as independent field replications.



Figure 2. Washing of maize-whorl samples (A) and spectrophotometric analysis of the washing solution (B).



Figure 3. Measurement of the sampled maize-whorl leaf area using ImageJ software.

According to Scudeler et al. (2004), absorbance values, when related to different concentrations of the dye (tracer), allow the establishment of a linear equation used to indicate the concentration of the dye (mg L^{-1}) captured by the target during application. By correlating the concentration of the dye in the sample washing solution with that obtained in the spray solution, it was possible to establish the volume captured by the target using Equation 1.

$$V_{dep} = \frac{C_f \times V_f}{C_i} \quad (1)$$

where:
V_{dep}= volume of spray solution retained by the target (mL);
C_f= tracer concentration in the washing solution obtained from the calibration curve (mg L^{-1}); V_f= final volume of the washing solution (30 mL);
C_i= tracer concentration in the spray solution (3000 mg L^{-1}).

To establish a comparison standard, a calibration curve was developed using the spray solution collected directly from the sprayer, which was stored in a dark plastic container and kept refrigerated (4-8°C). A calibration curve was prepared using aliquots of the original spray solution diluted with distilled water. Aliquot volumes of 0, 0.2, 0.4, 0.6, 0.8, and 1.0 µL were used to prepare the calibration standards. The absorbance values obtained at 630 nm were related to the corresponding final tracer concentrations to estimate the tracer concentration in the washing solutions. The experimental deposition (µL cm^{-2}) on the corn whorls was determined by Equation 2.

$$DEP_{exp} = \frac{V_{dep} \times 1000}{A} \quad (2)$$

where:
DS_{exp}= experimental spray deposition (µL cm^{-2});
V_{dep}= deposited spray volume (mL);
A= sampled target area (cm^2);
1000 = conversion factor from mL to µL.

The estimated surface dose of each active ingredient was calculated by relating the experimentally determined spray deposition to the simulated active ingredient concentration in the spray solution. This calculation was performed for each deposition observation and each simulated concentration according to Equation 3.

$$DS_{exp} = \frac{DEP_{exp} \times C_{AI}}{10^6} \quad (3)$$

where:
DS_{exp}= estimated active ingredient surface dose deposited on the target (µg a.i. cm^{-2});
DEP_{exp}= experimentally determined spray deposition (µL cm^{-2});
C_{AI}= simulated active ingredient concentration in the spray solution (µg a.i. L^{-1});
10^6= conversion factor from µL to L.

The resulting $DS_{exp\ values}$ represent the theoretical amount of active ingredient deposited per unit of leaf area for each simulated spray-solution concentration. These values were subsequently compared with the corresponding LD_{80} values obtained from the literature.

Estimation of active ingredient surface dose and probability of reaching the LD_{80} reference value

The probability that the estimated deposited dose reaches or exceeds the LD_{80} reference value was determined by comparing the estimated deposited dose (DSexp) with LD_{80} values obtained from previously published studies for the three insecticides evaluated (Table 1).

Table 1. LD_{80} values reported in the literature for different *Spodoptera frugiperda* populations and insecticides.

Population	Population origin	LD_{80} (µg a.i. cm^{-2})	Active ingredient	Commercial product
SUS	Susceptible reference population	0.12	Indoxacarb	**Avatar®
SUS	Susceptible reference population	0.13	Metaflumizone	**Verismo®
SUS	Susceptible reference population	0.32	Chlorfenapyr	*Pirate®
BA-48	Roda Velha - BA	0.34	Indoxacarb	**Avatar®
BA-44	São Desidério – BA	0.63	Chlorfenapyr	*Pirate®
GO-RV	Rio Verde – GO	0.37	Metaflumizone	**Verismo®
GO-RV	Rio Verde – GO	0.46	Chlorfenapyr	*Pirate®
GO-RV	Rio Verde – GO	0.57	Indoxacarb	**Avatar®
MT-43	Lucas do Rio Verde – MT	0.50	Metaflumizone	**Verismo®

LD_{80} = lethal dose associated with 80% mortality; a.i. = active ingredient; SUS = susceptible reference population. The LD_{80} values were obtained from previously published laboratory dose–response studies and were used as toxicological reference values in the estimation of the probability of reaching or exceeding the LD_{80} reference value. Sources: Kanno et al. (2020) for chlorfenapyr and Kaiser et al. (2021) for indoxacarb and metaflumizone.

For each combination of spray volume, nozzle type, insecticide, and *Spodoptera frugiperda* population, the estimated deposited dose (DSexp) was compared with the corresponding LD_{80} value obtained from the literature. A binary response was assigned to each simulated spray-solution concentration: 1 when DSexp was equal to or greater than LD_{80}, and 0 when DSexp was lower than LD_{80}. The relationship between the simulated insecticide concentration and the estimated probability of reaching or exceeding the LD_{80} reference value was then modeled using

binomial regression with a probit link function, as shown in Equation 4.

$$\phi^{-1}(P_i) = \beta_0 + \beta_1 C_i \quad (4)$$

where:
P_i= estimated probability of reaching or exceeding the LD_{80} reference value at the *i*th simulated concentration; ϕ^{-1}= inverse cumulative distribution function of the standard normal distribution, corresponding to the probit link function; β_0= intercept of the probit model; β_1= slope coefficient of the probit model; C_i= simulated concentration of the active ingredient in the spray solution at the *i*th concentration level (µg a.i. L^{-1}).

The estimated probability for each simulated concentration was obtained using Equation 5.

$$P_i = \phi (\beta_0 + \beta_1 C_i) \quad (5)$$

where:
P_i= estimated probability of reaching or exceeding the LD_{80} reference value at the *i*th simulated concentration; ϕ= cumulative distribution function of the standard normal distribution;
β_0= intercept of the probit model; β_1= slope coefficient of the probit model; C_i= simulated concentration of the active ingredient in the spray solution (µg a.i. L^{-1}).

For each simulated concentration, DSexp was calculated considering the experimentally determined spray deposition and the corresponding active ingredient concentration in the spray solution. The binary response used in the probit model was classified as 1 when DSexp ≥ LD_{80} and as 0 when DSexp < LD_{80}. Therefore, the model-estimated probability represents the likelihood that the estimated deposited dose reaches or exceeds the LD_{80} reference value reported for each insecticide and pest population.

The quality of the fit was evaluated based on the estimation of the coefficients (β_0 and β_1), standard errors, the chi-square statistic (χ^2), and the respective significance values. For each spray volume and nozzle scenario tested, summary tables were generated containing the model parameters and the estimated concentration values needed to achieve specific probability levels, including the respective confidence intervals (95%), ensuring that they remained between 0 and 1.

Comparison with published LD_{80} values allowed each simulated condition to be classified according to whether the estimated deposited dose reached the toxicological benchmark. A condition was classified as "LD_{80} benchmark reached" when DSexp ≥ LD_{80} and as "LD_{80} benchmark not reached" when DSexp < LD_{80}.

For each insecticide and spray volume, the minimum and maximum concentrations of active ingredient in the spray solution were calculated from the minimum and maximum doses recommended on the product label. The recommended dose of active ingredient per hectare was divided by the corresponding spray volume of 50 or 100 L ha^{-1}. The resulting label-derived concentration ranges were 3,840–4,800 µg a.i. L^{-1} and 1,920–2,400 µg a.i. L^{-1} for chlorfenapyr at 50 and 100 L ha^{-1}, respectively; 900–1,200 µg a.i. L^{-1} and 450–600 µg a.i. L^{-1} for indoxacarb; and 3,840–4,800 µg a.i. L^{-1} and 1,920–2,400 µg a.i. L^{-1} for metaflumizone. Eleven concentration levels were used in the probabilistic modeling for each insecticide and spray-volume combination. These levels comprised a zero-concentration reference, five concentrations distributed within the label-derived range, including its lower and upper limits, and five hypothetical concentrations above the upper label-derived limit, extending to three times the maximum concentration.

The concentrations above the label-derived range were included exclusively as numerical scenarios to describe the behavior of the fitted probit curve and to estimate the concentration associated with different probability levels. These concentrations were not applied in the field and should not be interpreted as agronomic recommendations. All practical interpretations were restricted to concentrations derived from the registered minimum and maximum label doses.

When the modeled concentration required to reach a specified probability exceeded the maximum label-derived concentration, the result was interpreted as an indication that the evaluated spray application condition provided insufficient estimated deposition to reach the LD_{80} benchmark within the registered dose range. Increasing the insecticide dose above the registered label recommendation was not considered an acceptable management strategy. Under such conditions, improvements in spray deposition should be sought through nozzle selection, spray-volume adjustment, and appropriate application conditions.

Data analysis

Analysis of variance

The experiments conducted in 2022 at the V4 growth stage and in 2023 at the V8 growth stage were analyzed separately. Spray coverage, droplet density, and spray deposition were subjected to analysis of variance according to a randomized complete block design arranged in a split-plot scheme, with four replications. Spray volume was assigned to the main plots, and nozzle type was assigned to the subplots. The subplot receiving each spray volume × nozzle combination was considered the experimental unit. The water-sensitive papers and maize whorls collected within each subplot were considered subsamples. For spray coverage and droplet density, the mean of the four water-sensitive papers was used as the subplot value in the analysis of variance. For spray deposition, the mean of the five sampled maize whorls was used as the subplot value. The assumptions of normality of residuals and homogeneity of variances were evaluated using the Shapiro–Wilk and Levene tests, respectively. After confirming the assumptions, the data were subjected to analysis of variance using the F-test. When significant effects were detected, treatment means were compared using Tukey's test at $P \leq 0.05$.

Probit regression analysis

For the regression models used to relate spray deposition to the estimated probability of reaching or exceeding the LD_{80} reference value, the individual values obtained from the subsamples were used rather than the subplot means. This procedure preserved the variation observed among the targets sampled within each spray volume × nozzle combination and provided the range of deposition values required for the estimation of responses

under the simulated spray-solution concentrations.

The individual measurements represented subsample observations collected within the experimental subplots. Therefore, their use in the regression analysis did not change the number of field replications or the experimental design adopted for the analysis of variance. The analysis of variance was based on subplot means, whereas the regression models used the individual subsample measurements to characterize the relationship between spray deposition, simulated spray-solution concentration, and estimated probability of reaching or exceeding the LD_{80} reference value.

RESULTS AND DISCUSSION

Spray coverage, droplet density, and tracer-derived spray deposition

At the V4 growth stage in 2022, spray coverage was affected by nozzle type and spray volume (Table 2). At 50 L ha^{-1}, the hollow-cone nozzle provided greater coverage than the twin flat-fan and single flat-fan nozzles. When the spray volume was increased to 100 L ha^{-1}, coverage increased for all nozzle types, with the hollow-cone and single flat-fan nozzles providing greater coverage than the twin flat-fan nozzle.

A similar response was observed at the V8 growth stage in 2023. The hollow-cone nozzle provided greater coverage at 50 L ha^{-1}, whereas the hollow-cone and single flat-fan nozzles showed the highest coverage values at 100 L ha^{-1}. The greater coverage obtained with the hollow-cone nozzle may be associated with the production of smaller droplets, which increases the number of droplets distributed over the target surface. However, smaller droplets may also be more susceptible to drift, particularly under unfavorable environmental conditions (MACIEL et al., 2017; ANTUNIASSI; BOLLER, 2019).

Although greater spray coverage may favor products whose performance depends on extensive target contact, coverage alone does not demonstrate biological efficacy. The response of an insecticide also depends on its physicochemical properties, mode of action, target susceptibility, and the amount of active ingredient deposited on the target.

Table 2. Spray coverage (%) as affected by spray volume and nozzle type at the V4 growth stage in 2022 and the V8 growth stage in 2023.

Coverage (%)						
Spray volume (L ha^{-1})	Hollow cone		Twin flat-fan		Single flat-fan	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
	V4					
50	15.10 aA	6.90	6.15 aB	3.19	8.72 aB	4.48
100	30.40 bA	11.03	16.76 bB	7.02	26.43 bA	9.03
	V8					
50	14.47 aA	6.66	5.83 aB	3.01	8.29 aB	4.18
100	29.05 bA	10.31	16.23 bB	6.92	25.13 bA	8.82

*Means followed by the same lowercase letter do not differ from each other within columns, and means followed by the same uppercase letter do not differ from each other within rows according to Tukey's test at $p \leq 0.05$.

Droplet density was also influenced by nozzle type and spray volume (Table 3). At the V4 growth stage in 2022, the hollow-cone and single flat-fan nozzles provided greater droplet densities than the twin flat-fan nozzle at 50 L ha^{-1}. At 100 L ha^{-1}, no significant differences were observed among nozzle types. At the V8 growth stage in 2023, the hollow-cone and single flat-fan nozzles also provided greater droplet densities at 50 L ha^{-1}. At 100 L ha^{-1}, the twin flat-fan nozzle showed a lower droplet density than the other nozzle types.

The twin flat-fan nozzle produced fewer than 80 droplets cm^{-2} under the 50 L ha^{-1} condition. Although there is no universal minimum droplet-density threshold applicable to all pesticides and targets, lower droplet density may reduce the uniformity of spray distribution, particularly for products that depend strongly on target coverage (MATTHEWS, 2008; NUYTTENS et al., 2007). Nevertheless, the present results describe the physical quality of the spray application and should not be interpreted as direct evidence of reduced pest control.

At the V4 growth stage in 2022, tracer-derived spray deposition differed among nozzle types and spray volumes (Table 4). At 50 L ha^{-1}, the hollow-cone nozzle provided greater deposition than the twin flat-fan and single flat-fan nozzles. Increasing the spray volume to 100 L ha^{-1} increased deposition for all nozzle types. Under this condition, the single flat-fan nozzle showed the highest numerical deposition value, although it did not differ significantly from the hollow-cone nozzle according to the mean-comparison results.

At the V8 growth stage in 2023, no significant differences in tracer-derived spray deposition were observed among nozzle types at 50 L ha^{-1}. At 100 L ha^{-1}, the hollow-cone nozzle provided greater deposition than the twin flat-fan and single flat-fan nozzles.

The differences observed between the V4 and V8 evaluations should be interpreted cautiously because the growth stages were evaluated in different growing seasons. Therefore, the observed variation may reflect both maize architecture and environmental differences between 2022 and 2023.

Table 3. Droplet density (droplets cm^{-2}) as affected by spray volume and nozzle type at the V4 growth stage in 2022 and the V8 growth stage in 2023.

Spray volume (L ha^{-1})	Droplet density (droplets cm^{-2})					
	Hollow-cone		Twin flat-fan		Single flat-fan	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
			V4			
50	182.23 aA	83.72	77.77 aB	44.60	128.61 aA	78.54
100	148.01 aA	31.74	119.45 aA	46.14	174.82 aA	61.23
			V8			
50	173.83 aA	79.64	74.17 aB	41.85	123.81 aA	77.04
100	142.03 aA	30.42	114.16 bB	43.09	166.07 aA	55.57

Means followed by the same lowercase letter do not differ from each other within columns, and means followed by the same uppercase letter do not differ from each other within rows according to Tukey's test at $p \leq 0.05$.

Table 4. Tracer-derived spray deposition (µL cm^{-2}) as affected by spray volume and nozzle type at the V4 growth stage in 2022 and the V8 growth stage in 2023.

Spray volume (L ha^{-1})	Tracer-derived spray deposition (µL cm^{-2})					
	Hollow-cone		Twin flat-fan		Single flat-fan	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
			V4			
50	3.50 aA	0.51	2.24 aB	0.49	2.42 aB	0.35
100	5.50 bA	0.78	4.33 bB	0.89	6.25 bA	1.01
			V8			
50	4.41 aA	0.38	4.17 aA	0.48	4.75 aA	0.78
100	6.79 bA	0.41	4.77 bB	0.54	4.59 bB	0.45

Means followed by the same lowercase letter do not differ from each other within columns, and means followed by the same uppercase letter do not differ from each other within rows according to Tukey's test at $p \leq 0.05$.

Overall, increasing the spray volume from 50 to 100 L ha^{-1} generally increased spray coverage and tracer-derived deposition, although the magnitude of the response depended on nozzle type and growing season. Greater spray volume increases the amount of liquid available to reach the target but may reduce operational capacity because of more frequent sprayer refilling and greater water demand. Conversely, reduced spray volumes may improve operational efficiency but require appropriate nozzle selection and calibration to maintain target coverage and deposition (SOUZA; CUNHA; PAVININ, 2012).

The hollow-cone nozzle generally provided high coverage and deposition, but its finer droplet spectrum may increase drift risk under unfavorable application conditions. Therefore, nozzle selection should consider both target deposition and spray-drift risk rather than application-quality indicators alone (ALVES et al., 2017).

These measured variables provide the physical basis for the subsequent modeling of the estimated probability of reaching the LD_{80} reference value. However, they do not independently demonstrate mortality of *Spodoptera frugiperda* or field efficacy.

Estimated probability of reaching the LD_{80} reference value under different nozzle types and spray volumes.

The estimated probability of reaching the chlorfenapyr LD_{80} reference value varied among nozzle types, spray volumes, and Spodoptera frugiperda populations at both the V4 growth stage in 2022 and the V8 growth stage in 2023 (Tables 5 and 6). These differences resulted from the interaction between experimentally determined spray deposition, simulated chlorfenapyr concentrations, and the LD_{80} reference value of each population. Therefore, the results represent model-derived estimates rather than direct measurements of insecticide efficacy.

The SUS, BA-44, and GO-RV populations differed in their previously reported susceptibility to chlorfenapyr, as indicated by their respective LD_{80} values. Consequently, the estimated probability of reaching the LD_{80} benchmark varied among populations even when the same spray-application condition and simulated insecticide concentration were considered.

At the V4 growth stage in 2022, the single flat-fan and hollow-cone nozzles generally produced high estimated probabilities of reaching the chlorfenapyr LD_{80} values within

the label-derived concentration range (Table 5). For most nozzle–population combinations, the modeled concentration associated with a 95% probability was lower than the maximum label-derived concentration. An exception was observed for some combinations involving the twin flat-fan nozzle at 50 L ha^{-1}, particularly for the BA-44 and GO-RV populations, for which the modeled concentration required to reach a 95% probability exceeded the registered concentration range.

At the V8 growth stage in 2023, a similar pattern was observed (Table 6). The single flat-fan and hollow-cone nozzles generally resulted in higher estimated probabilities than the twin flat-fan nozzle at 50 L ha^{-1}. Increasing the spray volume to 100 L ha^{-1} increased tracer-derived deposition and, consequently, increased the modeled probability of reaching the LD_{80} benchmark for the twin flat-fan nozzle.

The lower estimates obtained with the twin flat-fan nozzle at 50 L ha^{-1} were consistent with the lower spray coverage and droplet density observed under this application condition. Reduced deposition inside the maize whorl decreased the estimated active ingredient surface dose, particularly for populations with higher LD_{80} values.

When the concentration associated with a 95% probability exceeded the maximum label-derived concentration, the result was interpreted as evidence that the evaluated application condition was unlikely to reach the chlorfenapyr LD_{80} benchmark within the registered dose range. These modeled concentrations must not be interpreted as recommendations to increase the insecticide dose. Under such conditions, improvements should instead be pursued through nozzle selection, spray-volume adjustment, equipment calibration, and appropriate environmental conditions.

Comparisons between V4 and V8 should be interpreted cautiously because these growth stages were evaluated in different growing seasons. Therefore, differences between Tables 5 and 6 may reflect both crop architecture and environmental variation between 2022 and 2023.

Table 5. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on chlorfenapyr deposition at the V4 growth stage in 2022, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (3840 µg L^{-1})	[1]High. Lim. (4800 µg L^{-1})	
50	Single flat-fan	SUS	0.99	0.99	1671.0: 1672.7
		BA-44	0.96	0.97	3351.0: 3353.0
		GO-RV	0.98	0.99	2360.2: 2362.0
	Hollow-cone	SUS	0.99	0.99	1469.9: 1471.2
		BA-44	0.97	0.98	2791.1: 2792.6
		GO-RV	0.81	0.83	22328.4: 22329.0
	Twin flat-fan	SUS	0.99	0.99	1262.7: 1263.9
		BA-44	0.7	0.74	44331.0: 44331.6
		GO-RV	0.76	0.79	31539.9: 31540.5
			[1]Low. Lim. (1920 µg L^{-1})	[1]High. Lim. (2400 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	446.1: 448.4
		BA-44	0.99	0.99	859.7: 862.7
		GO-RV	0.99	0.99	635.1: 637.8
	Hollow-cone	SUS	0.99	0.99	630.1: 631.7
		BA-44	0.98	0.99	1205.9: 1207.9
		GO-RV	0.99	0.99	921.0: 922.8
	Twin flat-fan	SUS	0.97	0.98	1341.2: 1342.3
		BA-44	0.91	0.94	2626.8: 2628.0
		GO-RV	0.95	0.96	1887.0: 1888.1

[1]Lower and upper limits represent the minimum and maximum concentrations of the spray solution considering the minimum and maximum doses recommended on the Pirate® product label and the spray volume used; SUS = degree of susceptibility of *S. frugiperda* for a susceptible population (0.32 µg a.i. cm^{-2}); BA-44 = degree of susceptibility of *S. frugiperda* for a population obtained in São Desidério, State of Bahia, Brazil (0.63 µg a.i. cm^{-2}); GO-RV = degree of susceptibility of *S. frugiperda* for a population obtained in Rio Verde, State of Goiás, Brazil (0.46 µg a.i. cm^{-2}); [2]The range of values refers to a 95% confidence interval obtained from the probit models.

Table 6. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on chlorfenapyr deposition at the V8 growth stage in 2023, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (3840 µg L^{-1})	[1]High. Lim. (4800 µg L^{-1})	
50	Single flat-fan	SUS	0.99	0.99	1671.0: 1672.7
		BA-44	0.95	0.97	3608.0: 3610.4
		GO-RV	0.98	0.99	2360.2: 2362.0
	Hollow-cone	SUS	0.99	0.99	1262.7: 1263.9
		BA-44	0.96	0.98	2656.5: 2658.1
		GO-RV	0.98	0.99	1950.3: 1951.9
	Twin flat-fan	SUS	0.8	0.83	22328.4: 22329.0
		BA-44	0.7	0.74	44331.0: 44331.6
		GO-RV	0.76	0.79	31539.9: 31540.5
			[1]Low. Lim. (1920 µg L^{-1})	[1]High. Lim. (2400 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	446.1: 448.4
		BA-44	0.99	0.99	859.7: 862.7
		GO-RV	0.99	0.99	768.2: 770.2
	Hollow-cone	SUS	0.99	0.99	630.1: 631.7
		BA-44	0.98	0.99	1205.9: 1207.9
		GO-RV	0.99	0.99	921.0: 922.8
	Twin flat-fan	SUS	0.97	0.98	1398.6: 1399.7
		BA-44	0.94	0.97	2733.6: 2734.9
		GO-RV	0.95	0.96	1964.2: 1965.4

[1]Lower and upper limits represent the minimum and maximum concentrations of the spray solution considering the minimum and maximum doses recommended on the Pirate® product label and the spray volume used; SUS = degree of susceptibility of *S. frugiperda* for a susceptible population (0.32 µg a.i. cm^{-2}); BA-44 = degree of susceptibility of *S. frugiperda* for a population obtained in São Desidério, State of Bahia, Brazil (0.63 µg a.i. cm^{-2}); GO-RV = degree of susceptibility of *S. frugiperda* for a population obtained in Rio Verde, State of Goiás, Brazil (0.46 µg a.i. cm^{-2}); [2]The range of values refers to a 95% confidence interval obtained from the probit models.

Because larval mortality and crop injury were not measured, the results represent estimated probabilities of reaching literature-derived toxicological benchmarks and do not demonstrate chlorfenapyr efficacy or field control.

The estimated probability of reaching the indoxacarb LD_{80} benchmark varied among nozzle types, spray volumes, and *Spodoptera frugiperda* populations at the V4 growth stage in 2022 and the V8 growth stage in 2023 (Tables 7 and 8). These differences reflected the interaction between tracer-derived spray deposition, simulated indoxacarb concentrations, and the LD_{80} value reported for each population.

For the susceptible reference population, the single flat-fan and hollow-cone nozzles resulted in estimated probabilities ranging from 0.98 to 0.99 at 50 L ha^{-1}. At 100 L ha^{-1}, estimated probabilities for the susceptible population were at least 0.94 for all nozzle types. These values indicate a high modeled likelihood of reaching the LD_{80} benchmark within the label-derived concentration range.

For the BA-48 and GO-RV populations, however, the estimated probabilities remained below 0.90 across the label-derived concentration range, regardless of nozzle type or spray volume. These populations had higher literature-derived LD_{80} values than the susceptible reference population, requiring a greater estimated active ingredient surface dose to reach the same toxicological benchmark.

At 50 L ha^{-1}, the twin flat-fan nozzle generally produced the lowest estimated probabilities, which was consistent with its lower spray coverage and droplet density under this application condition. The hollow-cone nozzle generally produced higher estimates than the twin flat-fan nozzle, although the magnitude of this response varied among populations and growing seasons.

Increasing the spray volume to 100 L ha^{-1} increased the estimated probability for some nozzle–population combinations, particularly for the susceptible population. Nevertheless, the BA-48 and GO-RV populations did not reach an estimated probability of 0.95 within the label-derived concentration range. The model-estimated concentrations associated with a 95% probability were substantially greater than the maximum label-derived concentrations for these populations.Concentrations exceeding the registered range

were included only as numerical scenarios for describing the fitted probit curves. They must not be interpreted as recommendations to increase the indoxacarb dose. When the modeled concentration associated with a 95% probability exceeded the registered range, the application condition was interpreted as unlikely to reach the literature-derived LD_{80} benchmark within the legally permitted dose range.

Differences between the V4 and V8 results should be interpreted cautiously because the growth stages were evaluated in different growing seasons. Consequently, the observed variation may reflect differences in both maize architecture and environmental conditions between 2022 and 2023. Because larval mortality and plant injury were not evaluated, these results represent model-derived estimates of the probability of reaching toxicological reference values and do not demonstrate indoxacarb efficacy or field control.

The estimated probability of reaching the metaflumizone LD_{80} benchmark varied among nozzle types, spray volumes, and *Spodoptera frugiperda* populations at the V4 growth stage in 2022 and the V8 growth stage in 2023 (Tables 9 and 10). These differences resulted from the interaction between tracer-derived spray deposition, simulated metaflumizone concentrations, and the literature-derived LD_{80} value assigned to each population.

Table 7. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on indoxacarb deposition at the V4 growth stage in 2022, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (900 µg L^{-1})	[1]High. Lim. (1200 µg L^{-1})	
50	Single flat-fan	SUS	0.98	0.99	589.4: 590.6
		BA-48	0.41	0.58	3652.9: 3654.8
		GO-RV	0.54	0.70	2960.1: 2962.0
	Hollow-cone	SUS	0.98	0.99	476.8: 477.8
		BA-48	0.64	0.77	3106.1: 3107.8
		GO-RV	0.73	0.82	2444.1: 2445.8
	Twin flat-fan	SUS	0.74	0.79	7922.2: 7922.6
		BA-48	0.39	0.45	48329.5: 48330.2
		GO-RV	0.46	0.52	43716.3: 43716.9
			[1]Low. Lim (450 µg L^{-1})	[1]High. Lim. (600 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	160.1: 161.7
		BA-48	0.57	0.78	980.2: 983.2
		GO-RV	0.72	0.88	785.5: 788.4
	Hollow-cone	SUS	0.99	0.99	221.5: 222.6
		BA-48	0.51	0.69	1334.6: 1336.6
		GO-RV	0.61	0.77	1155.0: 1157.0
	Twin flat-fan	SUS	0.95	0.97	472.1: 472.9
		BA-48	0.32	0.45	3009.8: 3011.1
		GO-RV	0.40	0.54	2462.6: 2463.8

[1]Lower and upper limits represent the minimum and maximum active ingredient concentrations in the spray solution calculated from the minimum and maximum doses recommended on the Avatar® product label and the spray volumes used. SUS = susceptible reference population (LD_{80} = 0.12 µg a.i. cm^{-2}); BA-48 = population collected in Roda Velha, State of Bahia, Brazil (LD_{80} = 0.34 µg a.i. cm^{-2}); GO-RV = population collected in Rio Verde, State of Goiás, Brazil (LD_{80} = 0.57 µg a.i. cm^{-2}). [2]The reported ranges correspond to the 95% confidence intervals estimated by the probit models.

Table 8. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on indoxacarb deposition at the V8 growth stage in 2023, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (900 µg L^{-1})	[1]High. Lim. (1200 µg L^{-1})	
50	Single flat-fan	SUS	0.98	0.99	589.4: 590.6
		BA-48	0.41	0.58	3652.9: 3654.8
		GO-RV	0.54	0.69	2960.13: 2962.0
	Hollow-cone	SUS	0.98	0.99	476.8: 477.8
		BA-48	0.64	0.75	3106.2: 3107.8
		GO-RV	0.73	0.82	2444.2: 2445.8
	Twin flat-fan	SUS	0.74	0.79	7922.3: 7922.7
		BA-48	0.39	0.45	48329.6: 48330.2
		GO-RV	0.43	0.49	38969.3: 38969.9
			[1]Low. Lim. (450 µg L^{-1})	[1]High. Lim. (600 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	160.2: 161.7
		BA-48	0.56	0.78	980.2: 983.3
		GO-RV	0.72	0.88	785.5: 788.4
	Hollow-cone	SUS	0.99	0.99	221.6: 222.6
		BA-48	0.51	0.69	1334.7: 1336.7
		GO-RV	0.64	0.80	1090.9: 1092.9
	Twin flat-fan	SUS	0.94	0.96	472.2: 472.9
		BA-48	0.31	0.44	2943.7: 2945.3
		GO-RV	0.40	0.55	2370.6: 2372.1

[1]Lower and upper limits represent the minimum and maximum active ingredient concentrations in the spray solution calculated from the minimum and maximum doses recommended on the Avatar® product label and the spray volumes used. SUS = susceptible reference population (LD_{80} = 0.12 µg a.i. cm^{-2}); BA-48 = population collected in Roda Velha, State of Bahia, Brazil (LD_{80} = 0.34 µg a.i. cm^{-2}); GO-RV = population collected in Rio Verde, State of Goiás, Brazil (LD_{80} = 0.57 µg a.i. cm^{-2}). [2]The reported ranges correspond to the 95% confidence intervals estimated by the probit models.

At the V4 growth stage in 2022, the single flat-fan and hollow-cone nozzles generally resulted in high estimated probabilities of reaching the LD_{80} benchmark for the SUS, MT-43, and GO-RV populations within the label-derived concentration range (Table 9). For these nozzle treatments, the estimated probabilities ranged from 0.97 to 0.99 at 50 L ha^{-1} and were approximately 0.99 at 100 L ha^{-1}.

The twin flat-fan nozzle produced lower estimated probabilities at 50 L ha^{-1}, particularly for the MT-43 and GO-RV populations. For these combinations, the model-estimated concentrations associated with a 95% probability substantially exceeded the maximum label-derived concentration. Increasing the spray volume to 100 L ha^{-1} increased the estimated probabilities obtained with this nozzle, which was consistent with the greater tracer-derived deposition observed at the higher spray volume.

The response observed in the present study reinforces the finding that nozzle configuration and spray volume may alter the amount of spray deposited within the maize canopy. Previous studies conducted in maize have demonstrated that nozzle type, spray volume, and application technique influence spray deposition and the amount of insecticide reaching protected plant structures such as the maize whorl (TAVARES et al., 2017; ASSUNÇÃO et al., 2020).

At the V8 growth stage in 2023, the single flat-fan nozzle generally maintained high estimated probabilities across the evaluated populations (Table 10). The hollow-cone nozzle at 50 L ha^{-1} showed greater variation among populations, whereas increasing the spray volume to 100 L ha^{-1} increased the estimated probabilities for the evaluated nozzle–population combinations.

The twin flat-fan nozzle again produced the lowest estimates at 50 L ha^{-1}. The model-estimated concentrations associated with a 95% probability exceeded the maximum label-derived concentration for some population–nozzle combinations, particularly those involving populations with higher LD_{80} values or application conditions with lower tracer-derived deposition.

Table 9. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on metaflumizone deposition at the V4 growth stage in 2022, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (3840 µg L^{-1})	[1]High. Lim. (4800 µg L^{-1})	
50	Single flat-fan	SUS	0.99	0.99	694.6: 695.9
		MT-43	0.97	0.98	2622.3: 2624.1
		GO-RV	0.99	0.99	1902.2: 1903.9
	Hollow-cone	SUS	0.99	0.99	578.1: 579.2
		MT-43	0.99	0.99	2005.0: 2006.3
		GO-RV	0.99	0.99	1441.6: 1442.9
	Twin flat-fan	SUS	0.9	0.91	9491.4: 9491.9
		MT-43	0.74	0.78	35153.3: 35153.9
		GO-RV	0.79	0.82	26362.0: 26362.5
			[1]Low. Lim. (1920 µg L^{-1})	[1]High. Lim. (2400 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	183.2: 184.9
		MT-43	0.99	0.99	692.2: 694.9
		GO-RV	0.99	0.99	514.3: 516.7
	Hollow-cone	SUS	0.99	0.99	268.2: 269.3
		MT-43	0.99	0.99	975.9: 977.8
		GO-RV	0.99	0.99	725.9: 727.6
	Twin flat-fan	SUS	0.99	0.99	567.7: 568.5
		MT-43	0.93	0.95	2150.9: 2152.1
		GO-RV	0.96	0.97	1523.1: 1524.2

[1]Lower and upper limits represent the minimum and maximum active ingredient concentrations in the spray solution calculated from the minimum and maximum doses recommended on the Verismo® product label and the spray volumes used. SUS = susceptible reference population (LD_{80} = 0.13 µg a.i. cm^{-2}); MT-43 = population collected in Lucas do Rio Verde, State of Mato Grosso, Brazil (LD_{80} = 0.50 µg a.i. cm^{-2}); GO-RV = population collected in Rio Verde, State of Goiás, Brazil (LD_{80} = 0.37 µg a.i. cm^{-2}). [2]The reported ranges correspond to the 95% confidence intervals estimated by the probit models.

Differences among populations were associated with their previously reported susceptibility to metaflumizone. Kaiser et al. (2021) detected variation in the susceptibility of Brazilian *S. frugiperda* populations to metaflumizone and demonstrated the importance of population-specific toxicological benchmarks for resistance monitoring. In the present study, the susceptible reference population had the lowest LD_{80} value, whereas the MT-43 population had the highest value. Consequently, a greater estimated active ingredient surface dose was required for MT-43 to reach the same toxicological benchmark.

Kaiser et al. (2021) also reported relatively low overall variation in susceptibility to metaflumizone among the Brazilian populations evaluated. Therefore, the differences observed in the present modeling should not be interpreted as direct evidence of resistance in the MT-43 or GO-RV populations. They indicate only that the literature-derived LD_{80} values differed and consequently produced different modeled probabilities under the same spray-application conditions.

Concentrations exceeding the registered range were included only as hypothetical numerical scenarios for fitting the probit curves. These concentrations must not be interpreted as recommendations to increase the metaflumizone dose. When the concentration associated with a 95% probability exceeded the maximum label-derived concentration, the application condition was interpreted as unlikely to reach the literature-derived LD_{80} benchmark within the registered dose range.

Comparisons between the V4 and V8 results should be interpreted cautiously because the growth stages were evaluated in different growing seasons. Therefore, the differences observed between Tables 9 and 10 may reflect variation in crop architecture as well as environmental conditions between 2022 and 2023.

Because larval mortality, plant injury, and maize yield were not evaluated, these findings represent model-derived estimates of the probability of reaching toxicological reference values and do not demonstrate metaflumizone efficacy or field control.

Table 10. Estimated probability of reaching the *S. frugiperda* LD_{80} reference value based on metaflumizone deposition at the V8 growth stage in 2023, considering nozzle type, spray volume, label-derived spray-solution concentrations, and population susceptibility.

Spray volume (L ha^{-1})	Nozzle type	Population	Estimated probability of reaching or exceeding LD_{80}		[2] Model-estimated concentration associated with a 95% probability of reaching or exceeding LD_{80}
			[1]Low. Lim. (3840 µg L^{-1})	[1]High. Lim. (4800 µg L^{-1})	
50	Single flat-fan	SUS	0.99	0.99	694.6: 695.9
		MT-43	0.97	0.98	2622.3: 2624.1
		GO-RV	0.98	0.99	1902.2: 1903.9
	Hollow-cone	SUS	0.95	0.96	3806.3: 3807.0
		MT-43	0.92	0.94	5391.5: 5392.2
		GO-RV	0.97	0.98	1673.4: 1674.1
	Twin flat-fan	SUS	0.89	0.91	9491.4: 9492.3
		MT-43	0.74	0.77	35153.3: 35153.9
		GO-RV	0.79	0.81	26362.0: 26362.5
			[1]Low. Lim. (1920 µg L^{-1})	[1]High. Lim. (2400 µg L^{-1})	
100	Single flat-fan	SUS	0.99	0.99	183.2: 184.9
		MT-43	0.99	0.99	692.2: 694.9
		GO-RV	0.99	0.99	514.3: 516.7
	Hollow-cone	SUS	0.99	0.99	268.2: 269.3
		MT-43	0.99	0.99	975.9: 977.8
		GO-RV	0.99	0.99	725.9: 727.6
	Twin flat-fan	SUS	0.99	0.99	567.7: 568.5
		MT-43	0.93	0.95	2150.9: 2152.9
		GO-RV	0.96	0.97	1523.1: 1524.2

[1]Lower and upper limits represent the minimum and maximum active ingredient concentrations in the spray solution calculated from the minimum and maximum doses recommended on the Verismo® product label and the spray volumes used. SUS = susceptible reference population (LD_{80} = 0.13 µg a.i. cm^{-2}); MT-43 = population collected in Lucas do Rio Verde, State of Mato Grosso, Brazil (LD_{80} = 0.50 µg a.i. cm^{-2}); GO-RV = population collected in Rio Verde, State of Goiás, Brazil (LD_{80} = 0.37 µg a.i. cm^{-2}). [2]The reported ranges correspond to the 95% confidence intervals estimated by the probit models.

CONCLUSION

Spray volume and nozzle type affected spray coverage, droplet density, and tracer-derived spray deposition within the maize whorl. Increasing the spray volume from 50 to 100 L ha^{-1} generally increased spray coverage and deposition, although the magnitude of the response depended on nozzle type and growing season.

The single flat-fan and hollow-cone nozzles generally provided greater tracer-derived deposition than the twin flat-fan nozzle, particularly under application conditions in which the latter produced lower droplet density and coverage.

The modeled probabilities varied according to spray deposition, simulated insecticide concentration, and the literature-derived LD_{80} value assigned to each *Spodoptera frugiperda* population. Application conditions producing greater deposition generally resulted in a higher estimated probability of reaching the LD_{80} benchmark within the label-derived concentration range.

For some nozzle–population combinations, particularly those involving the twin flat-fan nozzle at 50 L ha^{-1} or populations with higher LD_{80} values, the concentration associated with a 95% probability exceeded the maximum label-derived concentration. Such results indicate limitations in the estimated deposition under those application conditions and must not be interpreted as recommendations to increase insecticide doses above the registered range.

Because larval mortality, plant injury, and maize yield were not evaluated, the estimated probabilities do not demonstrate insecticide efficacy or field control. The results should be interpreted as comparative model-derived predictions that may support the selection of spray-application conditions for further biological validation.

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