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OPTIMIZING BIOLOGICAL EFFICACY: ACTIVE INGREDIENT SELECTION AND CONCENTRATION WITH FULL HOLLOW CONE NOZZLE FOR *TETRANYCHUS URTICAE* KOCH CONTROL

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ABSTRACT

The precise selection and concentration of active ingredients play a pivotal role in enhancing the mortality of *T. urticae*. In the present study, various parameters including droplet size, spray coverage percentage, deposition, penetrability, and distribution uniformity across the eggplant canopy were examined. Two pesticides, Dichlorvos 50% ES and Sulfur 80% WG, were used at different concentrations (50, 75, and 100 ml l^{-1} for Dichlorvos and 1, 3, and 5 g l^{-1} for Sulfur) in this study. The whole experiment was set up following complete randomized block design consisting of three blocks. Pesticides were applied at the test concentrations to evaluate their efficacy. The key findings involved significant variations in *T. urticae* mortality based on the active ingredients and their concentrations. Higher concentrations, especially of dichlorvos, exhibited a significantly high *T. urticae* mortality compared to sulfur. However, the deposition of active ingredients on the leaves did not influence the droplet characteristics on the target for both types. Utilizing dichlorvos at elevated concentrations during spraying has the potential to enhance control efficacy.

Keywords: Eggplant, greenhouse, nozzle, orientation, *T. urticae* control

Eggplant, *Solanum melongena* L., holds significant agricultural importance globally, valued for its fruit which is predominantly utilized as a vegetable (Rotino *et al.*, 2023). In Iraq, eggplant cultivation is substantial, with an estimated 54,469 don (1 don=2500 square meters) in cultivated area in 2020, particularly prominent in the Basrah province, contributing 3,992.9 tons to the total production in an area of 8,514 km² (CSO, 2020). Greenhouse cultivation enables year-round eggplant production, requiring bed preparation in October and subsequent insecticide applications depending on the prevalent pests (FAO, 2003). Insecticide use is crucial in eggplant cultivation (Prado-Lu, 2015), particularly to combat *Tetranychus urticae* Koch, a major pest in greenhouse eggplant cultivation (Jakubowska *et al.*, 2022). Despite pesticide application, some insects survive and reinfest fields post-treatment, reducing pesticide efficacy (Sanchez-Bayo, 2021).

Commonly, insecticides such as dichlorvos and occasionally sulfur are utilized for pest control in greenhouse crops. Dichlorvos is approved for use on vegetative crops without detrimental effects on plant growth (Wang *et al.*, 2022). The correlation between active ingredients and their concentrations is crucial for effective pest control while minimizing environmental harm (EPA, 2024).

Optimal *T. urticae* control is achieved by directly spraying eggplants at a specific height above the plant's upper surface (Alper *et al.*, 2019). Canopy coverage poses a significant challenge to *T. urticae* control (Whitehead, 2017), as insufficient droplet penetration may leave some vegetation inadequately covered. Insufficient coverage limits *T. urticae* movement under leaf surfaces (Yeary *et al.*, 2018; Lewis and Hamby, 2020).

Achieving sufficient spray droplet coverage percentage is paramount for effective pest control (He *et al.*, 2022), influenced by the plant canopy structure, plant species, and growth stage (Musiu *et al.*, 2019). In eggplants, insecticide coverage varies significantly during plant development, with reduced deposition at lower canopy layers compared to upper layers (Hua *et al.*, 2020; Abraheem and Alheidary, 2022; Ibraheem and Alheidary, 2023). Reduced canopy protection may diminish insecticide exposure, uptake, and efficacy (Prado-Lu, 2015). Strategies to enhance spray penetration through plant canopies include increasing application volume and altering nozzle orientation (Derksen *et al.*, 2008; Foque *et al.*, 2012; Ibraheem and Alheidary, 2023). While nozzle type had minimal impact in a direct application study, increasing application volume potentially improved control efficacy. Nozzle effectiveness is also influenced by spray solution formulation, affecting canopy penetration (Alheidary *et al.*, 2014; Sijs and Bonn, 2020).

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Despite numerous studies on pesticide application in fields, limited information exists on droplet penetration into plant canopies (Le Bude *et al.*, 2012; Pan *et al.*, 2016; Zhu *et al.*, 2017). Hence, this investigation aimed to assess how eggplant characteristics, active ingredient types, and concentrations affect droplet size, coverage percentage, distribution, and penetration through the plant canopy to enhance *T. urticae* control efficacy.

MATERIALS AND METHODS

The field investigation was carried out at an agricultural research experimental station, where eggplants were cultivated in a greenhouse on October 1, 2022, with a plant to plant spacing of 40 cm within the same row. The greenhouse area accommodated three rows of eggplants with a row to row spacing of 100 cm. The main factors were the type of active ingredient (independent variable) and their concentrations (dependent variable). Two types of ingredients, Dichlorvos 50% ES and Sulfur 80% WG, were included in the study, each with three concentration levels (50, 75, and 100 ml l^{-1} for Dichlorvos and 1, 3, and 5 g l^{-1} for Sulfur).

To study the effect of different treatments against *T. urticae*, random eggplant leaves were selected to calculate the mortality percentage. The actual experimental unit size was 2.9 m^2 and all field experiments were conducted 209 days after planting. The average dimensions of the plants were approximately 66 cm in height and 30.5 cm in width. To assess droplet characteristics deposited on the plant leaves, Kromekote paper cards measuring 9 cm in length and 5.5 cm in width were positioned across three layers of the plant (upper, middle, and bottom) based on the selected plant height.

Brillant sulfa flavine (BSF) was added to water at a concentration of 1 g l^{-1} to enhance the visibility of water spots deposited on the paper cards. A single hollow cone nozzle mounted on the lance of a knapsack sprayer was utilized for spraying. The full hollow cone nozzle was chosen due to its potential to enhance spray canopy penetration and provide a smaller range of droplets for measuring the spray distribution pattern and biological effect. It was ensured that the selected nozzles were readily available to growers and compatible with existing sprayers without significant modifications. A spraying volume of 281 liters per hectare and a working pressure of 2 bar were maintained for all measurements, selected based on the operating pressure of 2 bar, which falls within the labeled range for the pesticide used.

The nozzle orifice height was approximately 25 cm from the bottom layers of the plant leaves. Tween-20 was added to the insecticide-water mixture to reduce surface tension and viscosity, facilitating better absorption into leaf tissues. Meteorological conditions during spraying application, including temperature (29°C) and relative humidity (65%), were measured using an anemometer (model MS 6252B). After spraying, the Kromekote papers were allowed to dry and then collected for transfer to the laboratory for analysis. The paper samples were divided into three layers at equal distances from the upper to bottom of the plant canopy and digitally scanned in grayscale at a resolution of 600 dpi. DepositScan software (USDA ARS, Wooster, OH) was employed for analyzing images, measuring droplet size, number of droplets per square centimeter, spray coverage percentage, and droplet deposition. Purified water was applied using a knapsack sprayer with a 16-liter tank capacity (Nexos Brand) for measuring droplet characteristics.

The relative spray deposition (RSD %) was determined based on the droplets present on both the inner and outer sections of the plant canopy, as per the following equation:

$$RSD = \frac{IC}{EC} \times 100$$

where, RSD is the relative spray deposition (dimensionless unit); IC is the internal spray coverage; EC is the external spray coverage.

The uniformity of spray droplets in the whole plant canopy was assessed by computing the coefficient of variation (CV) independently for each type of pesticide and its concentrations, using the following formula:

$$CV\ (\%) = \frac{SD}{\overline{X}} \times 100$$

where, SD is the standard deviation and X is the average of spray droplets. No surfactants were added during the spraying application alongwith the pesticide. To explore the impact of pesticide type and concentration on *T. urticae*-infested plant leaves, random leaves from various layers were collected post-spraying and placed into boxes, following the same procedure outlined in the spray coverage and penetration experiments. In a separate test, three concentrations of each pesticide were compared against a distilled water control. The application of different pesticide types at various concentrations was done on individual eggplants within a protected system, encompassing a plastic frame enclosed from all sides to prevent the transfer of spray droplets between treated and untreated plants.

Spray droplet treatments were utilized to examine the interaction between pesticide-laden spray and its concentration levels. The spraying operations were carried out using a knapsack sprayer with a total capacity of 16 liters. Following the methodology outlined by Henderson and Tilton (1955), *T. urticae* populations and their predators were assessed over a single season. Each experimental unit, comprising seven plants, occupied a plot measuring 2 meters in length and 0.66 meters in width, totaling an area of 1.32 square meters. The experimental design adopted for this study was a complete randomized block design (CBRD), involving three blocks.

Data collected from the droplet characteristics and control efficacy experiments were subjected to analysis of variance using Genstat software (Discovery edition 3). Least significant differences were computed for each treatment at a significance level of $p < 0.05$ to illustrate the significant variations between treatments.

RESULTS AND DISCUSSION

Spray droplet characteristics

Smaller and medium-sized spray droplets resulted in a higher coverage percentage and greater uniformity of distribution, especially in the lower layers of the plant. The production of *T. urticae* was lowest in case of the smallest and medium droplet sizes compared to other categories (Fig. 1). Conversely, larger spray droplet sizes exhibited less uniform distribution. The average droplet uniformity ranged from 14.79% to 17.39% depending on droplet size. Therefore, both droplet coverage percentage and deposition are affected by the size of the spray droplets.

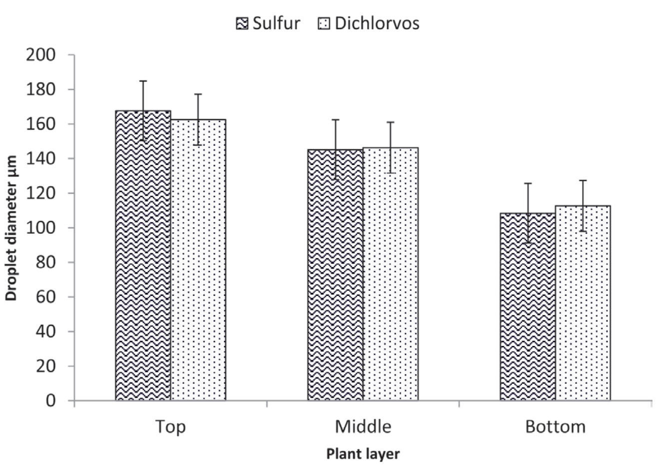

Fig. 1. Droplet size deposition of sulfur and dichlorvos on the vegetative plant layers

The impact of spray droplet size on the mortality of *T. urticae* was assessed using various active ingredients i.e. dichlorvos and sulfur. When holding these spray droplets at consistent sizes but adjusting their concentrations based on the active ingredient type, an inverse relationship between *T. urticae* mortality and spray droplet sizes was observed. The highest mortality of *T. urticae* (90.01%) was achieved when applying spray droplets with diameters ranging between 149-195µm. Consequently, an increase in spray droplet size generally led to a decrease in spray efficiency against *T. urticae*. Moreover, the efficiency of droplets containing minimal active ingredient content (0.01%) at maximum concentrations (100 ml l^{-1} and 5 g l^{-1}) reduced *T. urticae* populations by more than 14.69% and 22.60%, respectively, compared to droplets with lower concentrations after 14 days from the control, for dichlorvos and sulfur, respectively. Regarding other spray characteristics, such as droplet coverage measurements across different plant density layers, the percentage of spray coverage did not vary significantly between the two types of active ingredients and their concentrations, indicating consistent application of spray coverage (Fig. 2).

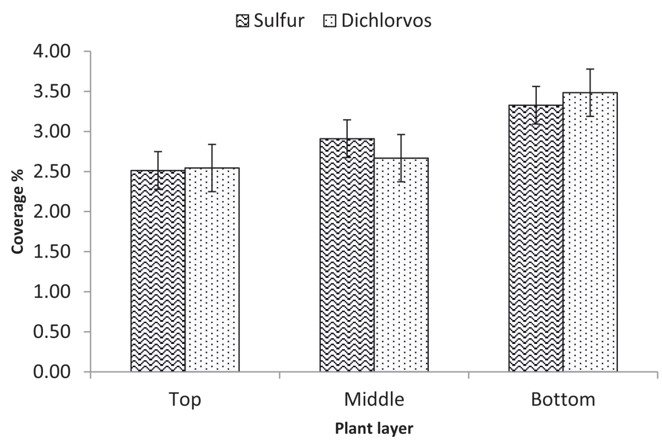

Fig. 2. Spray coverage percentage of two active ingredients across plant layers

In this study, it was observed that the coverage percentage decreased in the top layer of the plant in comparison to the bottom and middle layers. Regarding spray droplet penetration, there was a reduction of 140.28% in droplet penetration at the upper position and 76.41% at the middle position when compared to the bottom layer of the plant (Fig. 3).

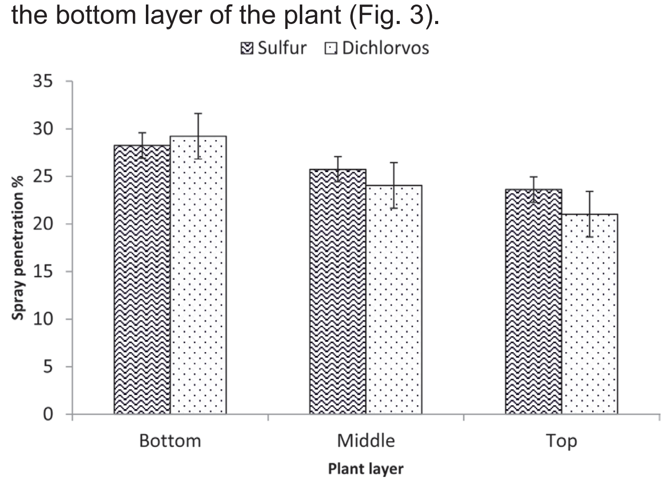

Fig. 3. Spray penetration percentage into plant layers for various active ingredients

Irrespective of crop density, distinct differences were observed between the bottom layers and the middle and top layers. The lower crop canopy exhibited over 64.13% and 62.79% deposition of sulfur and dichlorvos, respectively, compared to other parts of the plant canopy. Conversely, the upper canopy received less than 35.86% and 37.2% deposition of sulfur and dichlorvos, respectively (Fig. 4). The average spray droplet size measured 194 μm for sulfur and 195 μm for dichlorvos. Across all plant layers, spray deposits were consistently lower in the middle and top layers compared to the bottom layer, irrespective of the plant canopy density.

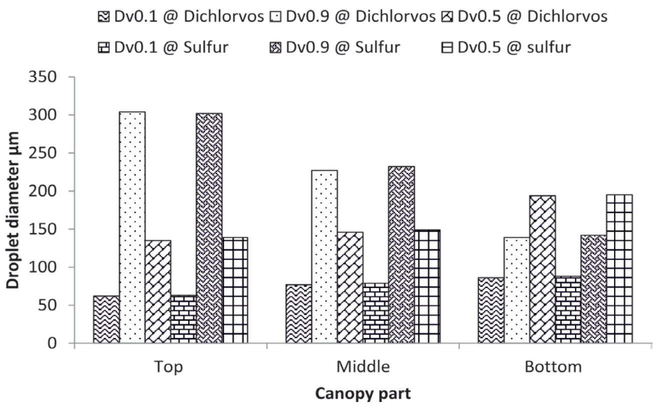

Fig. 4. Variation in spray droplet characteristics with different active ingredients across plant layers

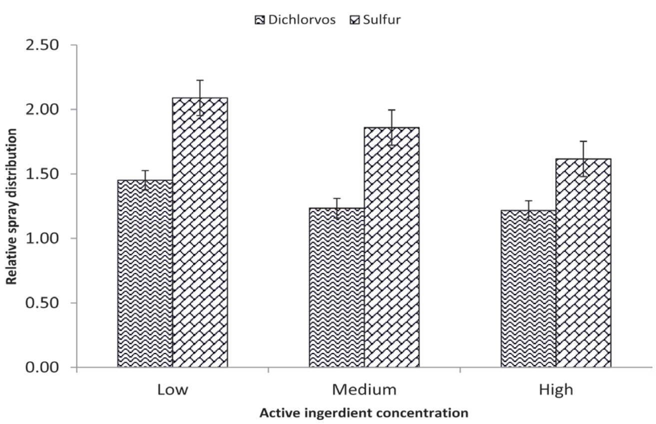

Fig. 5. Relative spray deposition values categorized by active ingredient type and concentration

Based on the relative spray deposition results (Fig. 5), the highest Relative Spray Deposition (RSD) values were consistently observed across both types of active ingredients and their concentrations, particularly notable at a concentration of 100 ml l^{-1} for dichlorvos. This finding aligns with previous reports regarding spray distribution evaluation throughout the plant canopy. Comparable RSD values were identified across the majority of treatments tested. Notably, the most significant mitigation in the *T. urticae* population of adult females was achieved using dichlorvos at a concentration of 100 ml l^{-1}. In field conditions, the mean mortality of *T. urticae* ranged from 76.20% to 90.01% after 14 days of spray treatments with the recommended dosage of sulfur and dichlorvos, respectively.

When dichlorvos was applied as the active ingredient, a notable interaction between spray characteristics and *T. urticae* mortality was observed, thereby impacting the survival potential of *T. urticae* (Fig. 4; Table 1). *T. urticae* specimens were confined to treated underside leaves from three plant layers (top, middle, and bottom) and exhibited lower survival rates compared to those exposed to leaves treated with active ingredients from the bottom layer of plants. Moreover, leaves from the top layers of plants showed higher survival rates compared to those from the bottom layers for both active ingredients utilized.

As depicted in Figure 6, smaller spray droplet sizes exhibited notably higher droplet density compared to other droplet sizes, consequently influencing the outcomes of spray deposition and droplet penetration.

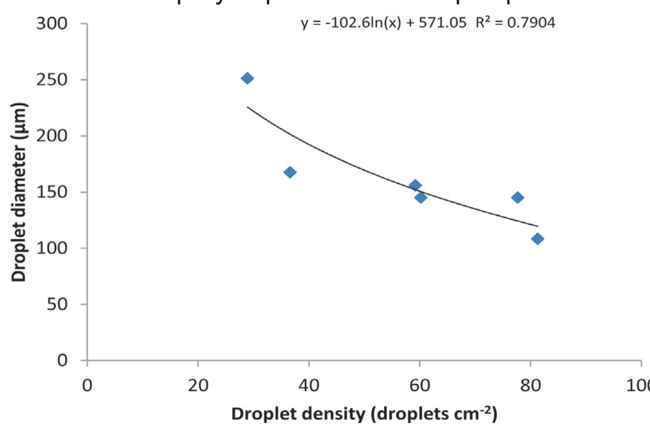

Fig. 6. Correlation of droplet density with droplet sizes and plant layers

The nozzle predominantly produced droplets (≥75%) concentrated within the range of <200 μm, and the spray droplets of each active ingredient type remained more stable within the range of 110–200 μm. The resulting *T. urticae* mortality fell within the range of 56.16–91.01% for dichlorvos and 25.05–76.20% for sulfur, respectively.

Evaluation of biological efficacy

Effect of active ingredient type on the T. urticae *mortality*

The percentage of *T. urticae* mortality (reduction percentage) exhibited significant variation among the collected samples ($P < .001$) (Table 1). One day following the initial spraying application of dichlorvos at a concentration of 100 ml l^{-1}, there was a 72.16% reduction in *T. urticae* population, with this percentage gradually increasing to 90.01% after 14 days compared to the control. In contrast, when sulfur was applied, the average mortalities ranged from 43.04% to 76.20% over periods of 1 to 14 days, respectively. The mortality percentage slightly rose to 76.20% after 14 days of sulfur application with an increased concentration. A gradual increase in mortality was observed for both dichlorvos and sulfur, particularly between days 7 and 14, reaching 90.01% and 76.20%, respectively, by the end of the experiment when using the higher concentration (Table 1).

Effect of active ingredient concentration

The application of dichlorvos led to an elevation in mortality percentages at concentrations of 100 ml l^{-1}. Furthermore, the results for other concentrations utilizing the same active ingredient differed significantly from those of the initial concentration (Table 1). The findings also demonstrated a linear rise in the mortality percentage, with coefficients of determination (R^2) of 0.93 and 0.91 for dichlorvos and sulfur, respectively.

All concentrations resulted in a reduction in the density of *T. urticae*, with up to a 90.01% decrease observed at the 100 ml l^{-1} concentration compared to other treatments. No significant differences were observed in percentage mortality among the concentrations, particularly evident between 7 and 14 days post-spraying application. For sulfur, the 5 g l^{-1} concentration also led to a reduction in the percentage of *T. urticae* compared to the control treatment, albeit not exceeding 77%. Previous studies have classified dichlorvos as toxic (Okoroiwu and Iwara, 2018), while sulfur has been regarded as environmentally non-toxic for controlling *T. urticae* (Riedl and Hoying, 1983). However, dichlorvos is known to rapidly decrease the density of *T. urticae*. In this investigation, sulfur yielded promising results, achieving significant reductions in live larval levels of *T. urticae* (Table 1) (Schmidt and Beers, 2014).

Effect of post-spraying treatment duration

The duration of residue presence in the field after control spraying significantly influences the percentage of *T. urticae* mortality. Mortality rates increased with the passing days post-spraying application, with a more pronounced increase observed with dichlorvos compared to sulfur. In the initial days following the spraying application, there was no notable increase in *T. urticae* mortality, particularly evident when using sulfur. This tendency possibly contributed to a resurgence of *T. urticae* following the application of this type of active ingredient.

The study revealed that the mortality rate of *T. urticae* following various spray treatments varied based on the type and concentration of the ingredients used. Dichlorvos demonstrated notable efficacy against *T. urticae*, particularly at higher concentrations. Application of the spray at maximum concentration (100 ml l^{-1}) effectively reduced *T. urticae* populations to low levels for approximately 14 days. Previous research has also highlighted the effectiveness and long term effect of dichlorvos against *T. urticae* (Teodoro *et al*., 2005; Okoroiwu and Iwara, 2018). However, there is a risk of field control failure and resistance development to this compound (Liburd *et al*., 2007). Nevertheless, dichlorvos showed promise for *T. urticae* management, with significantly lower relative abundance (14.69 and 22.60%) compared to sulfur after 14 days post-treatment, in contrast to water-only control. There is insufficient data available to assess the biological efficacy of sulfur relative to dichlorvos, necessitating further research for confirmation.

The effectiveness of using a contact-active ingredient with a coverage percentage ranging from 18 to 27% was found to be highly contingent on the specific pesticide employed for managing all stages of plant growth (Garcera *et al*., 2019). When targeting the

Table 1. Percentage mortality resulting from different active ingredients and concentrations

Active ingredient	Concentration of commercial product	Per cent larval mortality post-spray					Active ingredient's effect	Concentration product effect
		24h	48h	72h	7d	14d		
Dichlorvos	50 ml l^{-1}	56.19	67.46	73.86	78.19	78.48	77.73	60.27
	75 ml l^{-1}	60.77	76.18	82.19	85.75	86.99		68.90
	100 ml l^{-1}	72.16	81.87	86.87	89.04	90.01		74.75
Sulfur	1 g l^{-1}	25.05	47.82	57.47	55.99	62.15	58.21	60.27
	3 g l^{-1}	39.31	53.61	63.25	67.85	73.08		68.90
	5 ml l^{-1}	43.04	59.57	73.71	75.41	76.20		74.75
Time effect		49.42	64.42	72.83	76.40	76.79		
LSD ($p \leq 0.05$)		For % mortality: 3.16		For Concentration effect: 3.87		For time effect: 5.00		For active ingredient × time × concentration: 12.26

uppermost layer of the plant, where spray coverage was below 7%, this method of application might not provide adequate control of T. urticae, particularly within the inner layers of the plant canopy.

The density of droplets decreased progressively from 71.5 droplets cm^{-2} in the lower layers of the plant to 63.2 droplets cm^{-2} in the middle layers and 24.6 deposits cm^{-2} in the upper layers (Derksen *et al*., 2008). Similarly, reductions were observed in the penetration of spray droplets, with only 5% of the deposits reaching the bottom layer of the plant canopy. The smallest droplet sizes, particularly when droplet density falls below 10 droplets cm^{-2} in the upper layers of vegetative growth, may not provide adequate control of *T. urticae*. Despite the potential for increased droplet penetration in smaller, denser plant canopies, they still fall short of the recommended 20 to 30 droplets cm^{-2} for contact insecticides. The size and density of plant canopy leaves may influence spray coverage disparities between layers, impacting control efficacy, especially for *T. urticae* residing on the undersides of leaves. The larger bottom leaves of the plant canopy were found to be more significant for *T. urticae* control in this study.

Spraying on eggplant leaves, which are long and wide, facilitated greater collection of spray droplets in the bottom layer of the plant, thus enhancing *T. urticae* control. Sometimes, foliage can hinder spray droplet penetration and deposition within the plant canopy. To optimize droplet penetration, many pesticide applicators insert kromekote samples into the plant canopy, particularly in mid-to-large canopies. However, previous studies have shown that spraying from the bottom layers can increase spray penetration (Abraheem and Alheidary, 2022; Abraheem and Alheidary, 2023).

This study did not reveal any significant effect of the active ingredient type on droplet size, coverage percentage, penetration, or deposition. However, varying concentrations showed a potential for increased deposition with higher concentrations, resulting in enhanced *T. urticae* control, particularly in penetrating the bottom leaves of the plant canopy. The use of sulfur demonstrated relatively low larval mortality, with the highest efficacy (~77%) observed at a maximum concentration of 5 g l^{-1}, followed by 3 g l^{-1} and 1 g l^{-1}. While lower concentrations of dichlorvos and sulfur exhibited lower larval mortality compared to higher concentrations, they still outperformed the control treatment.

CONCLUSION

It can be concluded from this study that the use of dichlorvos, compared to sulfur, with a knapsack sprayer at the recommended dosage, effectively managed *T. urticae* on eggplants. Additionally, higher concentrations of dichlorvos resulted in increased mortality of *T. urticae*. A negative correlation was observed between the size of spray droplets deposited on the target and the average mortality of *T. urticae*, while a positive relationship existed between droplet density and *T. urticae* mortality. No discernible effect of the active ingredient type was observed in spray droplet size, coverage percentage, penetration, or deposition. The use of sulfur for control purposes resulted in relatively low larval mortality rates. Lower concentrations of both dichlorvos and sulfur exhibited lower larval mortality compared to higher concentrations, although these lower concentrations still outperformed the control treatment. Therefore, future studies might consider multiple spray applications at different concentrations throughout the vegetative growth stages of plants until harvest, while adhering to recommended dosages and considering environmental factors.

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Authors' contribution

Conceptualization and designing of the research work (MH, DS); Execution of experiments and data collection (MH, DS), Analysis of data (DS). All authors contributed to the article and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflict of interest.

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