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EVALUATION OF WHITEFLY CONTROL ON TOMATO CROP USING DIFFERENT NOZZLE ORIENTATIONS AND SPRAY APPLICATION VOLUMES

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ABSTRACT

Effective management of greenhouse whiteflies (*Trialeurodes vaporariorum*) is critical due to their high potential for crop damage and relative susceptibility to insecticidal control. This study was conducted to evaluate the impact of spray nozzle orientation, application volume, droplet size, and insecticide deposition on whitefly mortality and foliar spray coverage in tomato crops. Two insecticidal formulations *viz*. emamectin benzoate 5% and beta-cyfluthrin 5% EW were applied using three nozzle orientations and two spray volume rates. Results indicated a negative correlation between insect mortality in the upper plant canopy and increased spray application volume. At the same canopy level, spray droplet size was positively correlated with deposition (R^2 = 0.97), with small droplets depositing significantly less insecticide compared to medium and large droplets. However, droplet size did not have a significant effect on nymphal mortality. Furthermore, increasing the spray volume to 858.4 L·ha^{-1} did not enhance insecticide deposition or improve spray coverage. Canopy penetration by spray droplets was also unaffected by application volume but was significantly influenced by nozzle orientation. Overall, increasing spray application volume beyond 858.4 L·ha^{-1} is not recommended. Instead, reducing spray droplet size to approximately 128.53 µm may enhance whitefly control efficacy by improving canopy penetration and insecticide coverage within tomato crops..

Keywords: Droplet size, Insect mortality, Orifice direction, Spray penetration

Effective plant protection during the cultivation season is essential for improving both the quantity and quality of crop yields, particularly in greenhouse systems (FAO, 2013). However, the intensification of greenhouse agriculture, driven in part by the need to adapt to climate change, has led to a substantial increase in pesticide use, raising significant concerns regarding environmental sustainability and human health risks (Popp *et al.*, 2013). In Iraq, greenhouse cultivation plays a vital role in national vegetable production, with tomato crops occupying approximately 22,911.25 hectares and yielding an estimated 754,000.8 tons annually. This accounts for nearly 17.79% of the total area devoted to vegetable production across both open-field and protected environments. The southern region of Iraq, particularly Basrah Governorate, is a key center for greenhouse-based agriculture, contributing more than 28.2% of the country's total greenhouse production (CSO, 2023).

Tomato crop grown under greenhouse conditions is highly susceptible to insect pests, especially due to the crop's dense canopy, elevated temperatures, and high relative humidity. Among these pests, the greenhouse whitefly (*Trialeurodes vaporariorum*) is particularly problematic. It infests the vegetative stage of the tomato plant, weakening overall plant health and leading to significant yield losses. In severe infestations, heavy whitefly populations can result in complete crop failure (Elmhirst, 2006).

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Despite significant advancements in agricultural technology, pesticide application remains the primary method for pest control in greenhouse cultivation. In recent years, alongside integrated pest management (IPM) strategies, various techniques, such as the use of optimized nozzle types and targeted spray applications, have been tested to enhance pesticide deposition on intended targets while minimizing environmental impact due to spray drift (Zappalà *et al.*, 2012; ISO 22866, 2005; ISO 24253-1, 2015; Martelli *et al.*, 2020). These efforts aim to increase spray efficacy on foliar surfaces and simultaneously reduce pesticide usage.

As global food safety regulations have become more stringent, particularly for crops consumed daily, the implementation of effective IPM strategies has become increasingly important. However, IPM adoption remains limited in many agricultural systems (Papa *et al.*, 2018). For effective pest control, it is essential that pesticide droplets are deposited uniformly across the plant canopy and directed precisely at pest-infested zones, minimizing losses to the ground and drift caused by airflow. It is well established that foliar pesticide applications are generally inefficient, with only a fraction of the spray retained on plant surfaces and the remainder lost to the ground or surrounding environment (Garcera *et al.*, 2020).

In greenhouse environments, spray uniformity, pesticide retention, and off-target losses are influenced by multiple factors including sprayer type, nozzle configuration, application volume, leaf surface characteristics, and canopy density (Alheidary, 2018; Alheidary, 2019; Allagui *et al.*, 2018; Alheidary *et al.*, 2021). According to Braekman *et al.* (2009), many farmers increase spray application volumes in an attempt to achieve better canopy penetration and coverage. However, such practices may not yield proportional benefits and can exacerbate pesticide losses.

The application of pesticides in greenhouse systems is particularly critical and poses significant risks, especially to operators working in confined spaces (Jallow *et al.*, 2017). Sanchez-Hermosilla *et al.* (2021) found that inconsistent spray droplet distribution from knapsack sprayers results in inadequate canopy penetration, significant losses to the ground surface, and insufficient coverage on the undersides of leaves. These limitations often prompt farmers to reapply pesticides or increase spray volumes in response to poor pest control outcomes, thus increasing the risks of environmental contamination, operator exposure, and pest resistance development.

To address these issues, various spray techniques for knapsack sprayers have been developed to improve droplet distribution and reduce operator exposure and operational costs (Teka *et al.*, 2012; Li *et al.*, 2018; Nuyttens *et al.*, 2004; Balsari *et al.*, 2012; EPA, 2015). In dense greenhouse canopies, plant architecture significantly influences spray deposition. Boom sprayer systems, in particular, have been shown to offer superior coverage uniformity, enhanced droplet retention, and reduced off-target drift compared to traditional lance sprayers (Gil and Sinfort, 2005). Nevertheless, greenhouse operators often underestimate the labor demands and health hazards associated with manual knapsack spraying, especially in relation to pesticide exposure (Alheidary, 2017; Alheidary, 2018; Alheidary, 2019; Sanchez-Hermosilla *et al.*, 2021).

The spatial distribution of pest infestations within crop canopies is often irregular and rarely aligns with uniform spray patterns, even when using standardized application parameters. This variability is largely influenced by the type and orientation of spray nozzles used during pesticide application. The orientation of the nozzle can significantly affect droplet trajectory and deposition patterns, ultimately influencing pest control efficacy. Moreover, understanding the aggregation patterns of pest populations can inform the optimal direction and focus of spraying, enabling more targeted applications. High-density pest clusters, for instance, may necessitate concentrated nozzle coverage to enhance control efficacy (Sciarretta and Trematerra, 2014).

Achieving optimal control of whiteflies (*Trialeurodes vaporariorum*) in greenhouse-grown tomatoes requires precise calibration and adjustment of spraying equipment to ensure uniform droplet distribution and maximum foliar coverage. Proper spray coverage, particularly on the underside of leaves, where whiteflies typically reside, is critical for effective pest suppression. Therefore, selecting the appropriate spray application volume, in combination with an optimized nozzle orientation, is essential to improve droplet deposition, enhance coverage percentage, and promote deeper canopy penetration.

The primary objective of this study was to evaluate the influence of knapsack sprayer nozzle orientation and spray application volume on the spatial deposition of insecticide droplets within the tomato canopy. Specifically, this research aims to (1) assess the uniformity of spray distribution, (2) quantify droplet deposition and canopy penetrability, and (3) determine how these factors align with pest spatial distribution patterns. The ultimate goal is to improve whitefly management while minimizing pesticide overuse and off-target losses, thereby contributing to more efficient, sustainable pest control practices in greenhouse tomato production.

MATERIALS AND METHODS

Site characteristics of the greenhouse

The experiment was conducted during the 2021 growing season at the Agricultural Experimental Station, College of Agriculture, University of Basrah. The study took place in a greenhouse with a total area of 500 m², cultivated with tomato (*Lycopersicon*

Table 1. Main conditions inside the greenhouse

Location in the greenhouse	Parameter	
	Average temperature (°C)	Average relative humidity (%)
At the beginning	30.4	39.8
In the middle	31.7	40.7
At the end	30.5	39.7

esculentum Mill.) to evaluate the efficacy of whitefly (*Trialeurodes vaporariorum*) control under varying application conditions. The experimental design included six treatments comprising three nozzle orientations and two spray application volume rates. Each treatment was arranged in a randomized complete design (RCD) with three replicates per treatment, each occupying 10.5 m². An additional control group, sprayed with water only, was also replicated three times for comparative analysis. A single insecticide application was performed using a knapsack sprayer. The insecticide mixture contained Emamectin benzoate 5% and Beta-cyfluthrin 5%, applied at a concentration of 20 g per 100 L of water. Following treatment, three leaves from each replicate were randomly sampled from different canopy levels (upper, middle, and lower) across three separate plants. Samples were placed in labeled containers and transported to the laboratory for analysis.

Table 2 Knapsack speryer characteristics used in the study

Parameter	Values
Sprayer model	XF-16B
Empty weight for sprayer (kg)	3.4
Pump installation	Internal
Type of pump	Diaphragm
Maximum capacity of the tank (L)	16
Actual working pressure (bar)	2
Average operator speed (m.sec^{-1})	1.50

Whitefly nymph mortality was assessed using the Henderson and Tilton (1955) formula to account for natural mortality and treatment effects. Environmental conditions inside the greenhouse during the spraying process, including temperature and relative humidity, were monitored using an anemometer (model MS 6252B). The recorded data are presented in Table 1.

Characteristics of the sprayer and nozzle orientation

The knapsack sprayer with 16 liters tank capacity was used for spray applications. The characteristics of this sprayer are illustrated in table 2.

The sprayer's lance has a single Hollow cone nozzle affixed for spraying. The main characteristics of nozzle are described in table 3.

Table 3. Hollow cone nozzle characteristics

Parameter	Details
Spray pattern	Hollow cone
Spray angle (°)	80
Flowrate (l.min^{-1})	0.36
Droplet size	Fine size
Material options	Plastic
Application process	Chemical spraying
Spray distribution	Uniform on the periphery
Type of spray	Full spray pattern
Nozzle numbers	1
Actual working pressure (bar)	2

To evaluate spray distribution across the tomato crop canopy, three nozzle orientation configurations were tested in this study. As illustrated in Figure 1, the first configuration (Type A) involved a nozzle mounted vertically, directing the spray perpendicularly toward the crop canopy. The second configuration (Type B) applied the spray in an upward direction, from the base toward the top of the canopy (overturn orientation). The third configuration (Type C) combined both approaches, using a dual orientation that integrated the vertical (Type A) and upward (Type B) spray directions. All treatments were applied using a constant spray volume to ensure consistency across nozzle orientations.

The operating conditions such as worker speed, operating pressure, nozzle discharge, nozzle orientation, and spray application volume were measured during the spraying process. The operating parameters of this study are reported in Table 4. The treatments from 1 to 6 were repeated 3 times. Then the average of each treatment was independently calculated.

Spatial distribution pattern of whiteflies on the plant canopy

In order to describe the spatial pattern of whiteflies on the crop canopy, the tomato plant was divided into three parts (up, middle, and lower) as shown in Figure 2 to observe the spatial characteristics of insects in each part of the plant according to the total crop canopy.

Prior to pesticide application, leaves were randomly sampled from each canopy level (upper, middle, and lower) of the selected tomato plants. The leaves were

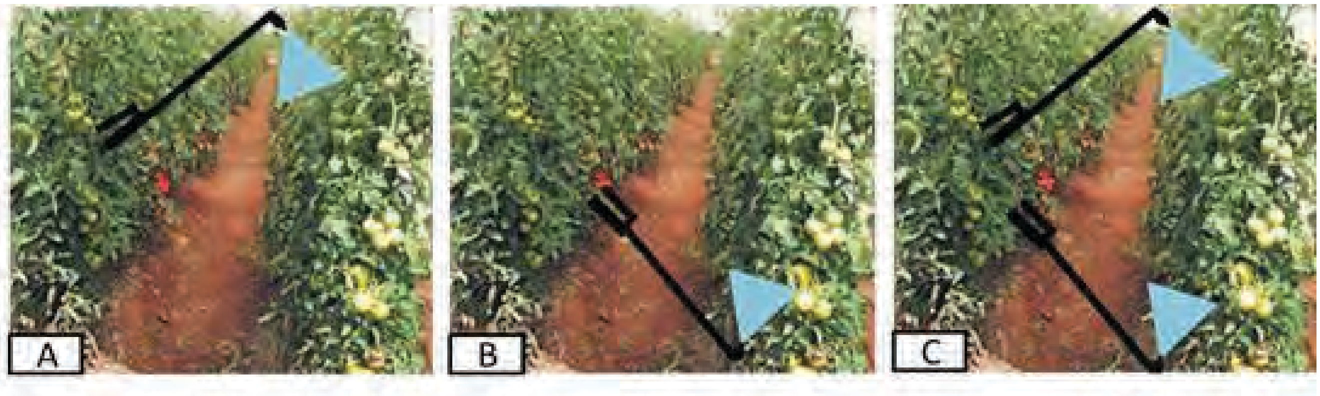

Fig. 1. Nozzle orientation towards tomato crop canopy

Table 4. General schematic for the experiments study

Treatment	Main parameters		
	Working pressure (bar)	Nozzle orientation	Application volume (l ha^{-1})
T_0	2	Control	429.2
T_1	2	A	429.2
T_2	2	B	429.2
T_3	2	C	429.2
T_4	2	A	858.4
T_5	2	B	858.4
T_6	2	C	858.4

T_0: control treatment (spraying with water only), T_1: Spraying perpendicular to the plant canopy at a lower application rate, T_2: Spraying from down to the plant canopy at a lower application rate, T_3: Combination of T_1+T_2 at a lower application rate, T_4: Spraying perpendicular to the plant canopy at a higher application rate, T_5: Spraying from down to the plant canopy at a higher application rate, T_6: Combination of T_1+T_2 at a higher application rate

immediately placed in dark containers to prevent insect dispersal and transported to the laboratory for analysis. Using a dissecting microscope, the actual number of whitefly nymphs present on the undersides of the leaves was counted to establish baseline infestation levels.

Three plants per replicate block were carefully examined for the presence of whitefly nymphs, specifically on the abaxial (underside) surface of the leaves. The pre-treatment counts for each treatment are presented in Table 5.

Table 5. Percentage distribution of whitefly nymphs across different canopy layers of tomato plants

Leaf location	Range of whitefly nymphs exist	Mean of nymphs	SD	Ratio of nymphs percent-age
Upper layer	22-49	29	8.73	22.51
Middle layer	21-77	46.33	15.86	35.97
LowerLayer	42-73	46.53	11.09	41.50

Whitefly nymphs are predominantly found on the lower leaves of tomato plants, whereas whitefly eggs tend to concentrate on the upper canopy. Reliable estimation of the whitefly population requires sampling leaves from multiple canopy regions. Detection of eggs and very young nymphs often necessitates the use of a 10× hand lens. However, egg counts were excluded from this study's analysis.

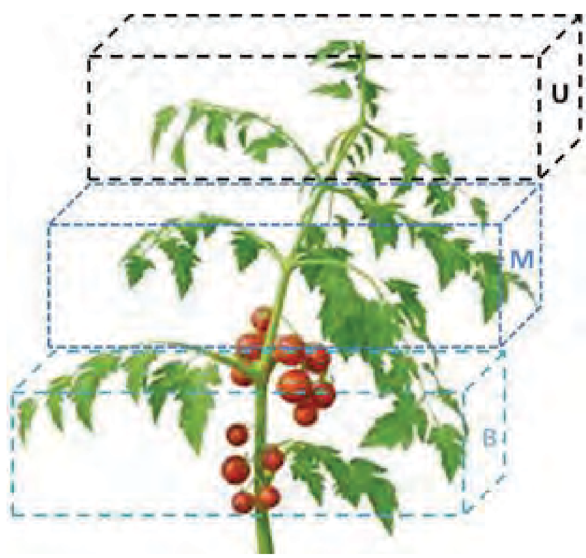

Fig. 2. Schematic representation of tomato canopy (U: Upper; M: Middle; B: lower)

Measurement of the spray droplets' characteristics

Kromekote papers were employed to measure spray droplet sizes by attaching them to tomato leaves prior to pesticide application. Following the spray event, droplets deposited on the Kromekote papers were allowed to dry on the plant surface for a minimum of 15 minutes. After drying, the papers were carefully collected and stored in a dark container to prevent degradation, with environmental parameters, including air temperature, relative humidity, and wind speed, recorded at the time of sampling. In the laboratory, droplet characteristics were analyzed using DepositScan software (Zhu, 2011). This software quantified key parameters such as droplet size distribution, average droplet diameter, total area coverage by spray spots, number of spots per unit area, and total spray volume deposited. The extracted data were exported to Microsoft Excel for further processing and calculation of droplet sizes. The actual spray droplet diameter was determined using the formula provided by Zhu (2011).

$$D = 0.95 d_s^{0.910} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$ds = \sqrt{\frac{4A}{\pi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where, A is the area of spot.

To determine the precise diameter of the spray droplets, the final equation used is (Zhu, 2011):

$$d = 1.06 A^{0.455} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

An additional set of Kromekote cards was horizontally positioned at three different canopy levels of the tomato plants to assess the extent of spray droplet penetration into the plant canopy.

Spray deposition, coverage percentage, and spray penetration

Additional Kromekote paper samples were strategically placed within the tomato plant canopy to evaluate key spray parameters, including spray deposition, spray coverage percentage, and droplet penetration through the canopy under varying nozzle orientations and spray application volumes. A fluorescent tracer, Brilliant Sulfa Flavine (BSF), was used at a concentration of 0.1% v/v to visualize and quantify spray deposition and coverage at different canopy levels. The tracer solution was thoroughly mixed into the spray tank prior to application. Spray deposition was measured as the volume of tracer deposited per unit leaf area ($\mu L \cdot cm^{-2}$). Spray coverage percentage was defined as the proportion of the leaf surface covered by the fluorescent tracer. Spray penetration was assessed by comparing droplet deposition between the outer and inner regions of the tomato crop canopy, allowing evaluation of how effectively spray droplets infiltrated the plant structure.

Efficacy of insectcide on whitefly

Following insecticide application in the greenhouse, leaf samples were randomly collected from each of the three canopy layers (upper, middle, and lower) of the tomato plants over a 14-day period post-spraying. Sampling was conducted in the morning, and three leaves were collected per canopy layer per replicate. The leaves were immediately placed in dark containers to prevent further insect activity and transported to the laboratory for analysis. The purpose of this sampling was to assess the impact of nozzle orientation and spray application volume on whitefly (*Trialeurodes vaporariorum*) population reduction. Whitefly nymph mortality was calculated using the Henderson and Tilton (1955) equation, which accounts for natural mortality in the control group and is a modified form of Abbott's formula:

$$\%\,Corrected\ Mortality = \left(\frac{\%T_a - T_b}{100 - \%T_b}\right) * 100 \quad \ldots (4)$$

where: T_a, is the mortality of collected insects after spray; and T_b, is the mortality of the whitefly per sampling unit before the spray (control).

Statistical analysis

Data on droplet deposition, spray coverage percentage, and insecticidal efficacy were analyzed using GenStat statistical software. Analysis of variance (ANOVA) was performed to evaluate the effects of nozzle orientation and spray application volume, as well as their interaction. Significant differences among treatment means were determined using the Least Significant Difference (LSD) test at the 0.05 probability level ($LSD_{0.05}$), allowing for comparison between treatments and identification of statistically meaningful effects.

RESULTS AND DISCUSSION

Effect of nozzle orifice orientation and application volume on the spray droplet characteristics

As illustrated in figures 3 and 4, nozzle orientation had a more pronounced effect on droplet distribution and droplet size compared to spray application volume. Among the treatments, the double nozzle orientation (combined vertical and upward spray direction) produced the most uniform and effective droplet distribution. While increasing spray volume alone had a relatively minor influence on spray droplet characteristics, its effect was more pronounced when combined with specific nozzle orientations, particularly the vertical configuration. Furthermore, transitioning the nozzle orientation from a vertical to an overturn (upward) position resulted in a significant reduction in the proportion of fine spray droplets. This suggests that nozzle direction plays a critical role in determining droplet size characteristics and their distribution across the canopy, with the combined nozzle orientation providing the most effective spray coverage.

The findings also indicated that pesticide type had no significant effect on spray droplet characteristics. This may be due to the similar physical properties, such as viscosity, surface tension, and density, shared by the insecticide formulations used, which are key determinants of droplet formation during atomization. When applied using the same nozzle system and under consistent operational conditions (i.e., spray pressure, nozzle type, and orientation), these physical properties resulted in comparable droplet behavior. This result aligns with previous research by Ozkan (2009) and Derksen *et al.* (2007), who reported that nozzle type, spray pressure, and nozzle orientation exert a significantly greater influence on droplet size and distribution than the formulation itself, provided that the spray volume and equipment setup remain constant.

Effect of the nozzle orifice orientation and application volume on the spray deposition and coverage percentage

Spray droplet deposition and spray coverage percentage were significantly influenced by both nozzle orientation and spray application volume. The highest spray deposition (2.88 μL·cm^{-2}) and coverage percentage (10.04%) were achieved using the overturn nozzle orientation combined with the lower application volume. A statistically significant interaction was also observed between nozzle orientation and canopy layer position ($p < 0.01$), based on Kromekote card analysis. As shown in Figure 5, Kromekote cards placed in the upper canopy were fully covered when the vertical nozzle orientation was used in combination with the higher application volume. In contrast, lower canopy samples showed minimal spray coverage (as low as 12.5%) under vertical orientation with low application volume. When comparing nozzle orientations at a constant application volume, the overturn orientation resulted in the least spray coverage in the upper canopy layer compared to other nozzle configurations.

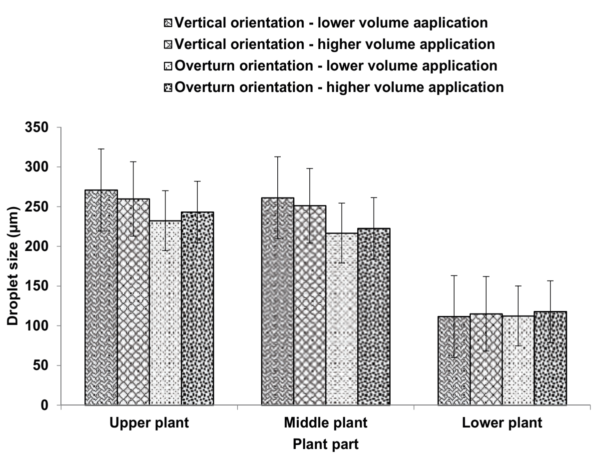

Fig. 3. **Mean droplet size (μm) measured at different canopy levels (upper, middle, and lower) of tomato plants as affected by spray application volume and nozzle orientation. Data reflect the interaction between nozzle configuration and application rate, showing variation in droplet deposition across plant parts.**

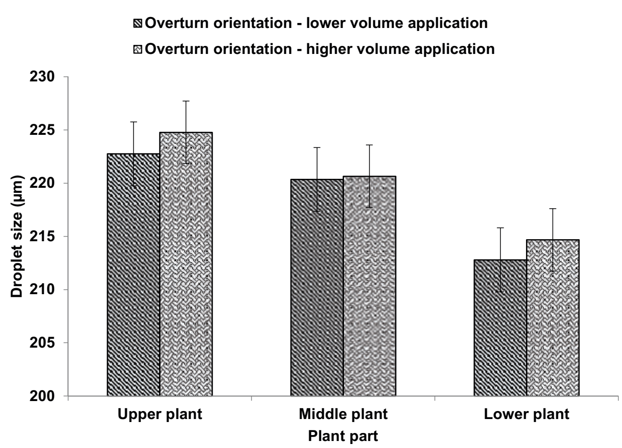

Fig. 4. **Mean droplet size (μm) at different canopy levels (upper, middle, and lower) of tomato plants under varying spray application volumes using the overturn nozzle orientation mode. The data illustrate how spray volume influences droplet size distribution within the canopy when sprayed from the base upward.**

Effect of the nozzle orifice orientation and application volume on the spray penetration through the plant canopy

Spray droplet penetration within the tomato plant canopy, measured across the upper, middle, and lower canopy layers under different nozzle orientations, is presented in Fig. 6. The highest penetration was observed when a combined nozzle orientation, utilizing both vertical and overturn spray directions, was employed. Although numerical differences in spray penetration ratios were evident among treatments, these differences were not statistically significant. The data indicated that spray droplet penetration generally increased in the upper canopy layers and with higher application volumes. The combined nozzle orientation at the second (higher) application volume resulted in the highest overall spray penetration. According to statistical analysis, the maximum canopy penetration (49.04%) was achieved using the combined orientation, while the lowest penetration was recorded under the vertical orientation alone. As illustrated in Figure 6, average droplet penetration improved with increasing spray volume. However, this trend was less pronounced or even reversed when using only the vertical nozzle orientation, which showed reduced ability to deliver droplets effectively into the deeper canopy layers.

Effect of nozzle orifice orientation and application volume on the mortality of whiteflies

Significant differences in insect mortality were observed and are summarized in Figure 7 as percent mortality. Based on the spray deposition data collected from leaves at various days post-application, the dataset was analyzed separately for each sampling time. The relationship between insecticide deposition and mortality percentage was evaluated by fitting regression models, with the best-fit equations presented in Table 6. These equations quantify the efficacy of pest control across different days after spraying, nozzle orientations, and application volumes. Additionally, Table 6 reports the correlation coefficients for each treatment, highlighting the influence of nozzle orientation and application volume on mortality rates over time.

The droplet density, spray deposition, and coverage percentage were strongly correlated with the droplet size produced by the hollow cone nozzles used in this study. Specifically, nozzles generating smaller volume median diameters ($D_{v0.5}$) produced a greater number of droplets, which in turn enhanced spray penetration into the tomato plant canopy (Fig. 3, 4, and 5). A significant interaction was observed between application volume and nozzle orientation affecting droplet density, spray deposition, and coverage percentage. However, no significant interaction was found between application volume and spray penetration, consistent with the observed droplet size trends (Fig. 6). These findings are in agreement with previous studies by Wolf and Daggupati (2009) and Hanna *et al.* (2009).

Although nozzle orientation had a substantial impact on spray deposition, coverage percentage, and

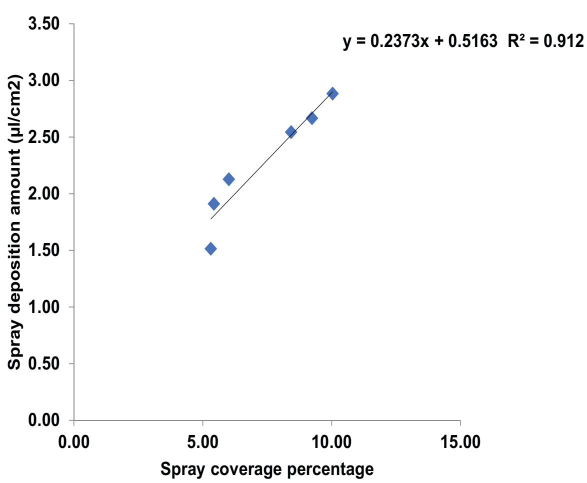

Fig. 5. Relationship between amount of spray deposition and coverage percentage

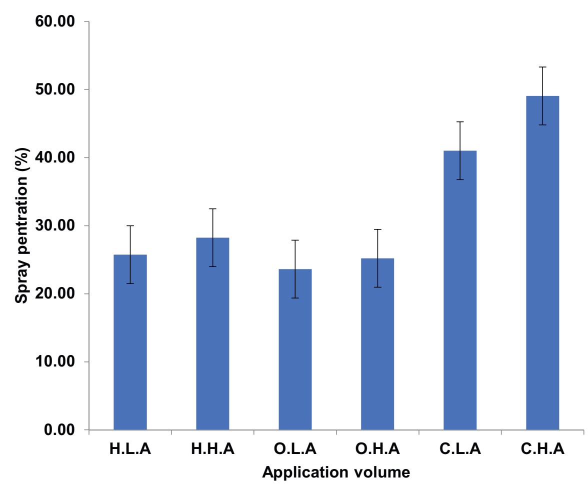

Fig. 6. Effect of spray penetration into the tomato plant canopy as influenced by nozzle orientation and spray application volume

H.L.A: Horizontal orientation at lower application; H.H.A: Horizontal orientation at higher application; O.L.A: Overturn orientation at lower application; O.H.A: Overturn orientation at higher application; C.L.A: Combination orientation at lower application; C.H.A: Combination orientation at higher application

Table 6. Correlation of whitefly mortality (%) with nozzle orientation and spray application volume across different tomato canopy layers (upper, middle, and lower) at various days after spraying

Treatment	Plant layer	Best-fitting equations for estimating per cent mortality	R^2 value
Vertical orientation-lower application	Upper	$CE=-0.0107x^2+0.2364x+0.4215$	0.93
	Middle	$CE = -0.0094x^2 + 0.218x + 0.4874$	0.96
	Lower	$CE= -0.0117x^2 + 0.2297x + 0.4949$	0.92
Vertical orientation-Higher application	Upper	$CE = -0.0096x^2+0.2085x + 0.3946$	0.80
	Middle	$CE = -0.0037x^2 + 0.1094x + 0.6949$	0.98
	Lower	$CE = -0.0056x^2 + 0.1353x + 0.5559$	0.78
Overturn orientation-lower application	Upper	$CE = -0.0064x^2 + 0.1775x + 0.5087$	0.97
	Middle	$CE = -0.0051x^2 + 0.1279x + 0.5474$	0.85
	Lower	$CE = -0.0108x^2 + 0.2414x + 0.3839$	0.98
Overturn orientation-Higher application	Upper	$EC = -0.0102x^2 + 0.2115x + 0.525$	0.97
	Middle	$EC = -0.0083x^2 + 0.1821x + 0.514$	0.93
	Lower	$EC = -0.0093x^2 + 0.2205x + 0.4628$	0.99
Combination orientation-lower application	Upper	$EC = -0.0086x^2 + 0.1957x + 0.4237$	0.88
	Middle	$EC = -0.0099x^2 + 0.2183x + 0.4376$	0.94
	Lower	$EC = -0.0096x^2 + 0.206x + 0.4245$	0.85
Combination orientation-Higher application	Upper	$EC = -0.0045x^2 + 0.1295x + 0.6392$	0.96
	Middle	$EC = -0.0042x^2 + 0.1128x + 0.6672$	0.82
	Lower	$EC = -0.0064x^2 + 0.1672x + 0.6281$	0.99

droplet penetration, as observed from the Kromekote paper collectors placed on the plant canopy, spray coverage percentage was most strongly correlated with droplet size (Fig. 3, 4, 5, and 6).

The results of this study clearly demonstrated that nozzle orifice orientation significantly influenced spray deposition, coverage percentage, and penetration across the tomato plant canopy. These effects were closely correlated with droplet size, as shown in Fig. 3, 4, 5, and 6. This finding aligns with previous work by Chen *et al.* (2020), who reported that spray droplet quality and size were key determinants of spray coverage, droplet density, and canopy penetration. In the present study, the combined nozzle orientation (vertical + overturn) produced higher spray deposition and coverage percentages than either vertical or overturn orientation alone, particularly when sampling at multiple canopy levels.

The finer droplets generated under this configuration may have enhanced penetration due to their smaller size and the moderate crop canopy density, which may not have posed a strong barrier. These observations are supported by Zhu *et al.* (2004), who showed that nozzle angle adjustment improved canopy penetration in crabapple trees, and by Chen *et al.* (2020), who demonstrated enhanced spray penetration using optimized droplet sizes. However, other studies have reported improved penetration with coarser droplets (Zhu *et al.*, 2004; Derksen *et al.*, 2008; Hanna *et al.*, 2009), suggesting that optimal droplet size may be crop-dependent due to structural differences among plant canopies (e.g., tomato vs. peanut or soybean).

Our findings reinforce the importance of placing collectors at multiple canopy positions, rather than relying on a single location (e.g., lower canopy) as

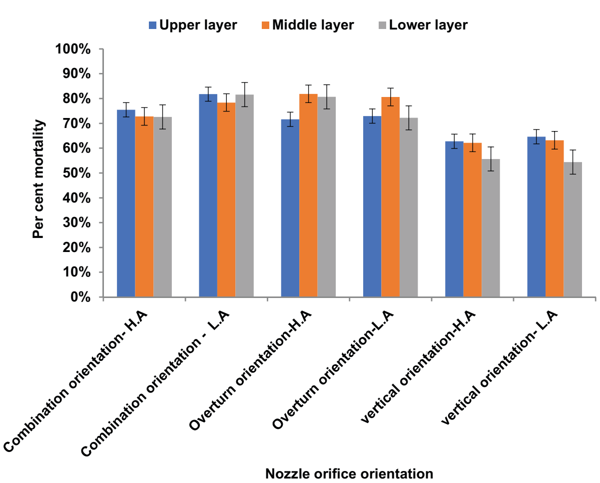

Fig. 7. Control efficacy as influenced by different nozzle orifice orientations and spray application volumes (H A: Higher Application; L A: Lower Application)

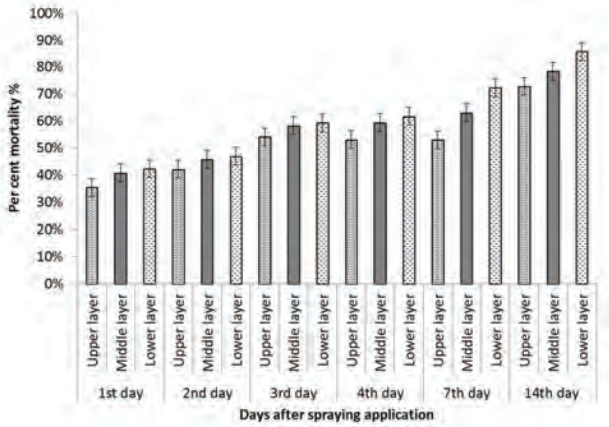

Fig. 8. Percentage mortality of whiteflies over time at different tomato plant canopy layers (upper, middle, and lower), illustrating the temporal efficacy of treatments following pesticide application

in studies such as Wolf and Daggupati (2009), which limits the ability to capture overall canopy deposition dynamics. In this experiment, fine to medium-sized droplets were associated with increased deposition, coverage, and droplet density per unit area, with nozzle orientation and spray application rate being key influencing factors. While the interaction between nozzle orientation and application volume significantly affected droplet deposition and coverage, application volume alone had limited influence on penetration (Fig. 6). Increasing application volume did not uniformly enhance spray deposition or coverage across all canopy levels. However, as shown in Fig. 7, the combined nozzle orientation achieved high control efficacy even with lower application volumes, demonstrating that effective spray distribution can be obtained without excessive pesticide use.

This has practical significance: lower spray volumes can reduce the risk of off-target drift, environmental contamination, and pesticide wastage. Although smaller droplets produced at lower volumes are generally more drift-prone, appropriate nozzle selection and orientation can mitigate this risk while maintaining adequate coverage. Moreover, this study found no loss in deposition or coverage at lower volumes when the combined nozzle orientation was used, indicating that spray volume could be reduced without compromising pest control efficacy. Alheidary *et al.* (2021) similarly emphasized the relevance of nozzle orientation and spray parameters in enhancing insecticide efficiency. Supporting this, Musiu *et al.* (2019) reported that reduced deposition and coverage under lower application rates did not necessarily impair control efficacy, depending on the pesticide formulation.

While our data show that spray deposition and coverage decreased with reduced application volume (Fig. 6), acceptable control levels were still achieved, particularly with combined nozzle orientation. Between application rates of 429.2 L·ha^{-1} and 858.4 L·ha^{-1}, spray coverage improved by 47.51% (Table 4; Fig. 5), highlighting the role of higher volumes in improving distribution, especially in lower canopy areas often shielded from direct spray. These observations are in agreement with earlier studies (Derksen *et al*., 2007; Dario *et al.*, 2020), which found that increasing spray volume enhances deposition and uniformity. However, this must be balanced with environmental concerns and the risk of reduced efficacy due to droplet coalescence at excessively high volumes.

To summarize, droplet size was a critical factor influencing deposition, coverage percentage, and canopy penetration. A droplet size of approximately 243.21 µm yielded the highest deposition (3.91%), while larger droplets (~224.77 µm) still provided acceptable deposition (3.28%) and density (19.13 droplets·cm^{-2}). Importantly, spray application rate influenced deposition and coverage, but its impact on droplet density was more dependent on nozzle orientation than volume alone.

Future studies should stratify these findings to determine biologically efficient thresholds for spray coverage and deposition. Understanding the minimum effective coverage required for pest control will support more precise selection of nozzle technology and orientation, allowing growers to reduce spray loss and environmental impact while maintaining pest control efficacy.

CONCLUSION

This study demonstrated that both nozzle orientation and spray application volume significantly influenced spray characteristics and the control efficacy of whiteflies when using a knapsack sprayer in greenhouse-grown tomato crops. The most effective treatment was the combination nozzle orientation (a mix of vertical and overturn directions) applied at a lower spray volume (T_5), which yielded the highest droplet deposition and spray coverage, particularly outperforming the higher-volume application (T_6).

Lower spray volumes not only improved whitefly mortality rates but also enhanced spray efficiency, reduced water usage, and minimized environmental impact, making them a more sustainable option. In contrast, the vertical nozzle orientation alone resulted in insufficient coverage of the lower leaf surfaces, where whitefly nymphs typically concentrate, thereby reducing control efficacy.

The findings suggest that optimizing nozzle orientation, specifically using a combined vertical and overturn setup, while applying a reduced spray volume can significantly enhance pesticide performance. Importantly, increasing spray volume did not correspond to improved insect control. Instead, reducing droplet size is recommended to improve canopy penetration and insecticide deposition, especially within the lower canopy zones where pests are more prevalent. These insights contribute to more targeted, efficient, and environmentally responsible pest management strategies in protected cropping systems.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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LITERATURE CITED

Alheidar M H R 2019. Influence of nozzle type, working pressure, and their interaction on droplets quality using Knapsack sprayer. *Iraqi J Agric Sci* **50**: 857-66. doi.org/10.36103/ijas.v50i3.702

Alheidary M R 2018. Effect of the operating pressure and nozzle height on droplet properties using knapsack sprayer. *Iraqi J Agric Sci* **49**(3): 360-66. doi.org/10.36103/ijas.v49i3.105

Alheidary M H R 2017. Performance of knapsack sprayer: Effect of technological parameters on nanoparticles spray distribution. *Int J Eng Trend Technol* **46**(4): 199-207. doi: 10.14445/22315381/ijett-v46p23

Alheidary M H, Hamed D S and Jaber F N 2021. Optimal efficacy of the essential nozzle characteristics and insecticide type for controlling cabbage aphid. *J Crop Prot* **10**(3): 511-22.

Allagui A, Bahrouni H and Sadak Y M 2018. Deposition of pesticide to the soil and retention during crop spraying: The art state. *J Agric Sci* **10**(12): 104-15.

Balsari P, Oggero G, Bozzer C and Marucco P 2012. An autonomous self-propelled sprayer for safer pesticide application in glasshouse. *Aspects Appl* Biol **114**: 1-8.

Braekman P, Foque D, Van Labeke M C, Pieters J G and Nuyttens D 2009. Influence of spray application technique on spray deposition in greenhouse Ivy pot plants grown on hanging shelves. *Hort Sci* **44**(7): 1921-27.

Chen S, Lan Y, Zhou Z, Ouyang F, Wang G, Huang X, Deng X and Cheng S 2020. Effect of droplet size parameters on droplet deposition and drift of aerial spraying by using plant protection UAV. *Agronomy* **10**, 195. doi:10.3390/agronomy10020195.

CSO 2023. Central statistical organization, Ministry of Planning, Iraq. http://cosit.gov.iq/

Dario G, Precipito L M B, de Oliveira J V, Lucilhia L V S and de Oliveira R B 2020. Application techniques of pesticides in greenhouse tomato crops. *Hortic Brasi* **38**(2): 146-52. https://doi.org/10.1590/S0102-053620200206

Derksen R C, Zhu H, Fox R D, Brazee R D and Krause C R 2007. Influence of nozzle type, spray volume, and canopy structure on spray deposition in nursery trees. *Hort Technol **17***(3): 326-32. https://doi.org/10.21273/HORTTECH.17.3.326

Derksen R C, Zhu H, Ozkan H E, Hammond R B, Dorrance A E and Spongberg A L 2008. Determining the influence of spray quality, nozzle type, spray volume, and air-assisted application strategies on deposition of pesticides in soybean canopy. *Trans ASABE* **51**(5): 1529-37.

Derksen R C, Zhu, H, Ozkan H E, Krause C R and Reding M E 2007. Coverage and drift produced by air induction and conventional nozzles used for nursery sprayers. *Hort Technol* **17**(3): 349-54. https://doi.org/10.21273/HORTTECH.17.3.349

Elmhirst J 2006. Crop profile for greenhouse tomato in Canada. Agriculture and Agri-Food Canada, Ontario, pp. 9.

EPA 2015. U.S. Environmental Protection Agency. https://www.epa.gov/.

FAO 2013. Good agricultural practices for greenhouse vegetable crops: Principles for Mediterranean climate areas. Available online: http://www.fao.org/3/a-i3284e.pdf

Garcera C, Fonte A, Salcedo R, Soler A and Chueca P 2020. Dose expression for pesticide application in citrus: Influence of canopy size and sprayer. *Agronomy* **10**: 1-30.

Gil Yand Sinfort C 2005. *Emissions of pesticides to the air during sprayer application: A bibliographic review*. *Atmos Environ* **39**(28): 5183-93. https://doi.org/10.1016/j.atmosenv.2005.05.019

Hanna H M, Robertson A E, Carlton W M and Wolf R E 2009. Nozzle and carrier application effects on control of soybean leaf spot diseases. *Appl Eng Agric* **25**(1): 5-13.

Henderson C F and Tilton E W 1955. Tests with acaricides against the brown wheat mite. *J Econ Entomol* **48**: 157-61.

ISO 2005. ISO 22866: Equipment for crop protection. Methods for field measurement of spray drift, Geneva, Switzerland, International Standards Organization.

ISO/TC 23/SC 6. ISO 24253-12015. Crop protection equipment-Spray deposition test for field crop.

Jallow M F A, Awadh D G, Albaho M S, Devi V and Thomas B M 2017. Pesticide knowledge and safety practices among farm workers in Kuwait: Results of a survey. *Int J Environ Res Public Health* **14**: 1-15.

Li Y J, Li Y F, Chen R H, Li X S, Pan C P and Song J L 2018. Evaluation of self-propelled high-energy ultrasonic atomizer on azoxystrobin and tebuconazole application in sunlit greenhouse tomatoes. *Int J Environ Res Publ Health* **15**(6): 1088. https://doi.org/10.3390/ijerph15061088

Martelli R, Lanzoni A, Maini S and Pezzi F 2020. Mechanical application of *Orius laevigatus* nymphs for the control of *Frankliniella occidentalis* in greenhouse crops. *Bull Insectol* **73**: 59-69.

Musiu E M, Qi L and Wu Y 2019. Spray deposition and distribution on the targets and losses to the ground as affected by application volume rate, airflow rate and target position. *Crop Prot* **116**: 170-80.

Nuyttens D, Windey S and Sonck B Art 2004. Comparison of operator exposure for five different greenhouse spraying applications. *J Agric Safety Health* **10**(3): 187-95.

Ozkan H E 2009. Reducing pesticide drift, Ohio State University Extension Bulletin. https://ohioline.osu.edu/factsheet/aex-520

Papa R, Manetto G, Cerruto E and Failla S 2018. Mechanical distribution of beneficial arthropods in greenhouse and open field: A review. *JAE* **49**: 81-91.

Popp J, Peto K and Nagy J 2013. Pesticide productivity and food security-A review. *Agron Sustain Dev* **33**: 243-55.

Sanchez-Hermosilla J, Rincon V J, Paez F C, Perez-Alonso J and Callejon-Ferre J 2021. Evaluation of the effect of different hand-held sprayer types on a greenhouse pepper crop. *Agriculture* **11**, 532. https://doi.org/10.3390/agriculture11060532

Sciarretta A and Trematerra P 2014. Geostatistical tools for the study of insect spatial distribution: Practical implications in the integrated management of orchard and vineyard pests. *Plant Protect Sci* **50**(2): 97-110.

Teka A, Yirefu F and Abadi Z 2012. Increasing the efficiency of knapsack sprayers by modifying a single nozzle sprayer into a low cost multi-nozzle sprayer. *Ethiopian J Weed Manage* **5**: 28-42.

Wolf R E and Daggupati N P 2009. Nozzle type effect on soybean canopy penetration. *Appl Eng Agric* **25**(1): 23-30.

Zappalà L, Manetto G, Tropea Garzia G, Emma G and Failla S 2012. Mechanical distribution of *Phytoseiulus persimilis* on chrysanthemum. *Acta Hortic* **952**: 793-800.

Zhu H 2011. A portable scanning system for evaluation of spray deposit distribution. *Comput Electron Agric* **76**: 38-43.

Zhu H, Dorner J W, Rowland D L, Derksen R C and OzkanH E 2004. Spray penetration into peanut canopies with hydraulic nozzle tips. *Biosyst Eng* **87**(3): 275-83.

Zhu H, Zondag R H, Derksen R C, Reding M and Krause C R 2008. Influence of spray volume on spray deposition and coverage within nursery trees. *J Environ Hortic* **26**(1): 51-57.