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Study on the Effectiveness of Spraying Operation in Greenhouses by Varying Nozzle Type under Different Pressures and Speeds

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Abstract

The objective of this study was for selecting the optimal nozzle type for the application of pesticides within greenhouse environments. This experiment was implemented on winter season tomato crop planted inside a greenhouse facility affiliated with the College of Agricultural Engineering Sciences (Baghdad University, Aljadiryah campus). Two nozzles were used APS80R 03C and AP120 03C and both were tested at 2 pressures (3.5 – 5 bar) and two operational speeds (1.54 – 2 km/hr) during the spraying operations. The results proved the AP120 03C nozzle took the first place, which could most probably be related to the lowest droplet size and droplet rate showed in the study. The highest coverage percentage was achieved when operating at pressure levels of 3.5–5 bar and speeds ranging between 1.54–2 km/hr. additionally, the lowest drift tendency was observed at the initial pressure level, with a drift rate of 18.33 droplets, and at the initial speed, with a drift rate of 32 droplets per test paper. These results highlight the effectiveness of the AP120 03C nozzle in optimizing spray application while minimizing undesirable drift. The second pressure level 5 bar and speed2 km/hr also influenced the number of droplets that exhibited drift tendencies from the same nozzle. For the AP120 03C nozzle, the total number of drifted droplets at the second pressure level was obtained as 50.17 and 36.50.

Keywords: ***nozzle type; Spray speed; pesticides; tomato crop; nozzle.***

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دراسة فاعلية الرش في البيوت المحمية بتغيير نوع الفوهة تحت ضغوط وسرع مختلفة

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الخلاصة

هدفت هذه الدراسة الى الاختيار الصحيح لنوع فوهة رش المبيدات داخل البيوت المحمية. التقنيات المستخدمة في عملية الرش نوعين من فوهات الرش APS80R 03C)) و AP120-03C)) ونوعين من الضغوط (3.5- 5) بار مع نوعين من السرع 1.54 - 2كم/سا. وكانت نتائج التجربة التي اجريت على محصول الطماطم الذي تم زراعته داخل احد البيوت المحمية التابعة لكلية علوم الهندسة الزراعية جامعة بغداد/الجادرية للموسم الشتائي اظهرت تفوق الفوهة من نوع AP120-03C)) في الحصول على اقل متوسط لحجم القطرات مع اعلى نسبة مئوية للتغطية عند استخدام الضغط (3.5- 5) بار والسرعتين 1.54 - 2كم/سا. واقل عدد للقطرات التي تميل للانجراف عند الضغط الاول وبمعدل 18.33 قطرة والسرعة الاولى بمعدل 32 قطرة، في حين كان للضغط الثاني 5 بار والسرعة الثانية 2كم/سا تأثير على عدد القطرات التي تميل للانجراف لنفس الفوهة فقد ازداد معدل عدد القطرات المنجرفة عند الضغط الثاني بمعدل 50.17 قطرة و36.50 قطرة عند السرعة الثانية.

الكلمات المفتاحية: *نوع الفوهة; سرعة الرش; المبيدات; محصول الطماطم; الفوهة.*

Introduction

Tomato is one of the most important crops of this century, having become a globally significant food crop. It ranks first among cultivated crops in terms of annual planted area, production volume, and consumption. Given that tomatoes are warm-season crops and due to the high demand for their production, there has been increasing interest in cultivating them in protected environments such as greenhouses (Picanço *et al.*, 2007). This crop is susceptible to agricultural pests at various growth stages, making it essential to implement an integrated pest management strategy to mitigate infestations and ensure optimal production (AlShabar *et al.*, 2021; Dumra *et al.*, 2024; Pretty, J and Bharucha, Z., 2015). Additionally, despite the high yield and year-round availability of tomatoes grown in greenhouses, their production comes with certain challenges that require careful management to maintain quality and sustainability (Aznar-Sánchez *et al.*, 2020). However, greenhouse cultivation creates favorable conditions for plant infections due to elevated temperatures and high humidity levels, which can promote the proliferation of pests and disease (McCartney *et al.*, 2018; Failla, and Romano. 2020). Advanced and emerging technologies provide innovative solutions to the complex challenges confronting the global food system (Al-Aani and Sadoon, 2023; Alwash and Al-Aani, 2023). These technological advancements are reshaping traditional agricultural practices, paving the way for a more sustainable and resilient future (Al-Sammarraie et al., 2023; Al-Aani, 2012). To protect crops, pesticides are applied weekly to ensure high-quality production (Belforte et al., 2011). However, maximizing the effectiveness of pesticides in pest control while minimizing their environmental impact, safeguarding workers' health, and producing pesticide residue-free crops requires careful management. Achieving these goals necessitates determining the amount of pesticide used during spraying by selecting appropriate equipment and spray nozzles (Luaibi & et **al**., 2025). The choice of *nozzle* significantly influences the droplet size and distribution of the sprayed solution, which is particularly critical in greenhouse applications Bargir et al., 2021; Biocca et al., 2021). Farmers still have many questions regarding the proper selection of spray nozzles, which play a crucial role in spray efficiency and are among the key factors determining the success of pest control measures. A nozzle is a term used to describe any device through which the spray liquid flows and is dispersed into droplets (Matthews *et al.*, 2014). In other words, it is a device that utilizes liquid pressure to increase its velocity and break it into droplets of varying sizes (PNR., 2009).. The primary function of a spray nozzle is to fragment the liquid into droplets of different sizes. Unfortunately, some of these droplets are large and carry a high concentration of pesticides, while others are very fine and prone to drift away from the target area an issue that must be avoided in any application (Matthews *et al.,* 2014).

Droplet size is one of the most critical parameters for spray quality (Robert *et al.,* 2013). It serves as an indicator of the average droplet size produced by the nozzle, directly influencing spray effectiveness. Proper droplet size ensures optimal coverage and deposition on the plant canopy while minimizing drift. Achieving this requires selecting the appropriate nozzle along with the correct spraying speed and pressure. As is well known, one of the key factors affecting droplet size is spray pressure. Higher spray pressure results in smaller droplets, which can enhance coverage. However, if droplet size falls below 150 microns, it becomes more susceptible to drift, reducing pesticide deposition on the target area and increasing environmental contamination risks (Cooley *et al.,* 2012). The loss of chemical substances due to drift reduces application efficiency, necessitating repeated spraying, which leads to financial losses and increased environmental contamination (Akesson and Yates., 1964). Drift refers to the movement of spray particles away from the target area shortly after pesticide application or within a short period thereafter. This reduces pesticide effectiveness and poses potential risks to plants and soil due to pesticide contamination (Greg R. Kruger, 2018; Jomantas *et al*., 2023; Vieira, *et al.,* 2019). Drift can occur in two forms: vapor drift, where pesticides evaporate into gases or fumes, and particle drift, which involves spray droplets being carried away during application. Particle drift primarily results from inadequate control of droplet size, which is directly influenced by nozzle design, nozzle orifice size, and operating pressure (Vieira, *et al.,* 2019). Another key factor affecting droplet size is spray speed. As noted by (Loux, *et al.,* (2013), increased spray speed can lead to the formation of smaller droplets, making them more susceptible to drift and reducing application efficiency.

The aim of this study is to evaluate different types of spray nozzles suitable for greenhouse applications to achieve an optimal droplet spectrum that ensures effective coverage while minimizing drift. This is accomplished by Proper selection of spray nozzle with appropriate operating conditions.

Materials and Methods

The experiment was conducted inside a greenhouse measuring 45 meters in length cultivated with a tomato crop with five rows, with a 90 cm spacing between rows. A locally manufactured automated sprayer of a (100) liter tank with an electric-powered piston pump that injects water into a spraying apparatus suspended a greenhouse. This works automatically by using a vertical arm to "fountain-spray, similar to a large-scale atomizer," to correctly disperse the pesticide and other liquids. A flexible plastic pipe was used to transfer liquid from the tank to the suspended apparatus. The two types of spraying nozzles used were APS80R 03C and AP120 03C.
A description of the orifices used is provided below:

Figure 1. The APS80R 03C nozzle, which operates at an 80° spray angle and a recommended pressure range of 3–20 bar. This nozzle is ideal for applying fungicides and insecticides due to its effective droplet distribution and coverage. (https://agroplast.pl/en_US/i/About/29)

Figure 2. The AP 120-03C nozzle, which operates at a 120° spray angle and functions within a pressure range of 2–5 bar. This nozzle produces small to medium-sized droplets, making it suitable for applications requiring fine droplet distribution and effective coverage (https://agroplast.pl/en_US/i/About/29).

Water-sensitive paper (WSP) was used to measure the amount of spray reaching the target, and the analysis was performed using the Deposit Scan image processing software, which rapidly evaluates the distribution of spray deposits on water-sensitive paper. This program has been developed (Zhu, Fox, 2011), and the dimensions of the paper were 7.5*2.5 cm, with four papers distributed on leaves on each plant. The height of each plant was one meter, and sensitive papers were distributed at heights of 10 cm, 40 cm (both sides), and 80 cm.

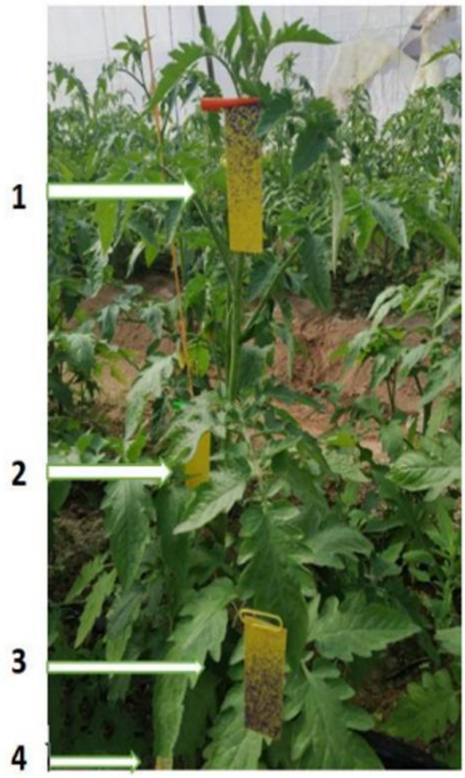


Figure 3. Distribution of sensitive papers on leaves**.**

1- Upper sensitive paper (at a height of 80 cm of total height of the plant).
2- Sensitive paper in the heart of the plant (at a height of 40 cm of the total height of the plant and in depth).
3- The sensitive paper was placed in front of the plant (at a height of 40 cm of the total height of the plant and in the face of the plant).
4-Lower sensitive paper (at a height of 10 cm of the total height of the plant).

Experiment Implementation

The experiment was conducted in a greenhouse at the Research Center of the College of Agricultural Engineering Sciences, University of Baghdad, where tomatoes were cultivated in five rows with a recommended plant spacing of 40 cm. The plants were trained using metal rods with perforations at the top, through which metal wires were threaded at 2-meter intervals for support. A Completely Randomized Design (CRD) was used to assess three factors: The spraying speed at two levels was 1.54 and 2 km hr-1 spray pressure at two levels (3.5 bar and 5 bar), and two types of spray nozzles (APS80R 03C and PA 120-03C), with three replications for each treatment.

The sprayer speed was determined using the following equation:
VP: Theoretical speed of the instrument (km/hr)
d: Distance (m)
T: Time (sec)
3.6: Conversion factor
The sprayer tank was filled with water, and the water-sensitive paper (WSP) was carefully attached to the plant leaves, as shown in Figure 3. After completing the spraying process, the sensitive papers remained fixed on the leaves until they dried completely. Once dried, they were collected and placed in envelopes for further analysis. The Deposit Scan software was then used to process and analyze the images to assess spray quality and deposition efficiency.

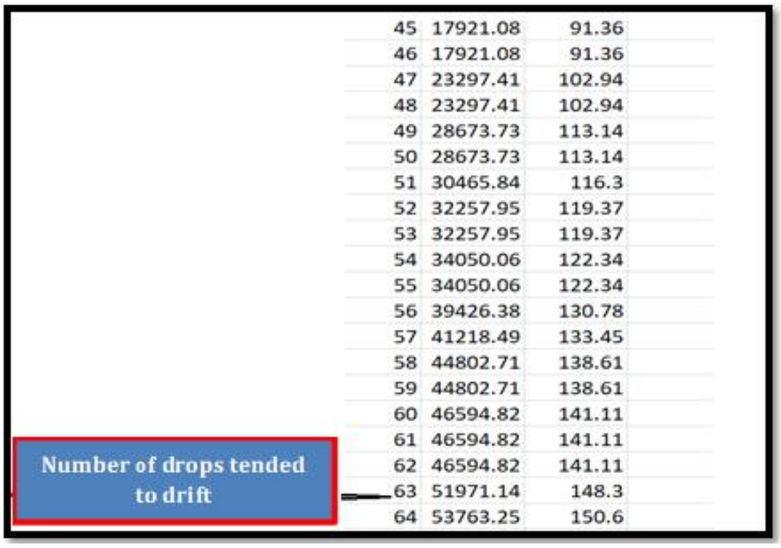
Characters studied

1. **Determination of Volume Median Diameter (VMD) (µm):**

Using the Deposit Scan software, three values of the volume median diameter (VMD) were obtained: DV_1µm, DV_5µm, and DV_9µm. The average of these values was used as the standard measurement, as it is the most commonly accepted parameter for droplet size analysis (Cunha and Marcal, 2012).

2. **Calculation of Spray Coverage (%)**

Spray coverage was determined as the percentage of the area covered by blue spray droplets relative to the total yellow background area of the water-sensitive paper (WSP). This measurement was performed using Deposit Scan software.



45	17921.08	91.36
46	17921.08	91.36
47	23297.41	102.94
48	23297.41	102.94
49	28673.73	113.14
50	28673.73	113.14
51	30465.84	116.3
52	32257.95	119.37
53	32257.95	119.37
54	34050.06	122.34
55	34050.06	122.34
56	39426.38	130.78
57	41218.49	133.45
58	44802.71	138.61
59	44802.71	138.61
60	46594.82	141.11
61	46594.82	141.11
62	46594.82	141.11
63	51971.14	148.3
64	53763.25	150.6

Figure 4. Excel Tab showing the number of drops tended to drift.

3. **Determination of Drift-Prone Droplets**

The number of droplets with an actual diameter of less than 150 µm was counted, as these droplets are more susceptible to drift. The Deposit Scan software was also used for this calculation. Figure 4 presents an Excel table summarizing the number of drift-prone droplets.

The Statistical Analysis System (SAS, 2018) software was used to analyze the data and evaluate the effects of different factors on the studied parameters. The experiment followed a factorial design (2 × 2 × 2) within a Completely Randomized Design (CRD). The significance of differences between treatment means was assessed using the Least Significant Difference (LSD) test to determine statistical significance.

Results and Discussion

1. Volume Median Diameter (VMD):

The results show that there was a significant effect of nozzle type, spray pressure, spray speed and interaction of nozzle type with spray pressure and spray speed on volumetric median diameter (Table 1). APS80R 03C nozzle resulted in the largest average size of droplets among other nozzles with an average value of 1139.08 µm, whereas AP 120-03C nozzle produced an average droplet of size 660.88 µm, this differentiation can be mainly due to the difference in spray angle of the nozzles. The APS80R 03C, narrower spray angle, resulted in larger droplets and the AP 120-03C with a wider spray angle produced smaller droplets. This result is in line with those reported by (Matthews, et al., 2014).

Also, it can be observed that for the effect of pressure of the spray, the lower pressure of the spray (3.5 bar) led to the greatest average dimension of the droplet (1029.63 µm), while the larger pressure (5 bar) produced smaller droplets (average of 770.33 µm), This confirms the general principle that lower spray pressure generates larger droplets, while higher pressure produces smaller droplets—provided that droplet size does not fall below 150 µm to minimize drift. The observed effects are consistent with those reported by Bargir et al. (2021) and Cooley et al. (2012).

The experimental results indicate larger droplet sizes, likely due to the coalescence of droplets occurring at the time of deposition onto the WSP. This coalescence effect causes larger droplet sizes to appear than their real size. This observation is consistent with findings reported by Subr *et al.* (2020) and Carroll (2017). The measurements were t**a**ken over a 2 cm² area of the water-sensitive paper. Statistical analysis revealed significant differences in spray speed, when speed increased from 1.54 km/h to 2 km/h. Average droplet size decreased from 972.83 µm to 827.13 µm. This indicates that high spray speed results in small drops, this is consistent with findings reported by Cavaliary et al. (2015).

In the case of two-way interaction between the nozzle type and the spray pressure on volume median diameter (VMD), the statistical analysis indicated that the AP 120-03C nozzle in 5 bars produced the smallest drops on average 604.67 µm. In contrast, in 5 bars the APS80R 03C nozzle produced large drops, with the average size of 936.17 µm.

For nozzle type-spray speed interaction, AP 120-03C nozzle combined with 2 km/h spray speed produced smaller droplets with an average size of 620.8 µm, which was smaller than the larger droplets produced by APS80R 03C nozzle with a spray speed of 2 km/h (1033.5 µm). The above results indicated that the droplet size was influenced by both nozzle type and operational parameters; thus, smaller droplets were formed at a higher spray speed and with wide spray angles, resulting in larger droplets at lower speeds and narrow spray angle.

Three -way interaction between nozzle type, spray pressure and spray speed showed a significant difference in volume median diameter. APS80R 03C nozzle, and lower pressure (3.5 bar) and combined with low speed (1.54 km/h), resulted the largest droplet size, the average of 1487.67 µm. In contrast, AP 120-03C nozzle, at high pressure (5 bars) and high speed (2 km/h), produced the smallest drop size, at average of 574.00 µm.

Table 1. Effect of nozzle type, pressure, spray speed, and their interactions on volume median diameter (VMD).

N Type of Nozzle	P Pressure (bar)	Speed V km/hr		N*P	Average-N
		1.54	2		
APS80R 03C	3.5	1487.67	1196.67	1342.17	1139.08
	5	1001.67	870.33	936.00	
AP120-03C	3.5	766.67	667.50	717.08	660.88
	5	635.33	574.00	604.67	

Value of LSD	LSD: N xP x V= 247.58*		LSD: NxP=214.59*	LSD:N=123.79*
NxV	Interaction between speed and nozzle type			-----
N1	1244.7	1033.5	LSD: NxV=214.59*	
N2	701.0	620.8		
VxP	Interaction between pressure and speed		Average –P	
P1	1127.2	932.1	1029.63	
P2	818.5	722.2	770.33	
Value of LSD	LSD: P*V=214.59 * *		LSD:P=123.79 *	
Average-Speed V ----	972.83	827.13		
Value of LSD	LSD: V = 123.79 *			

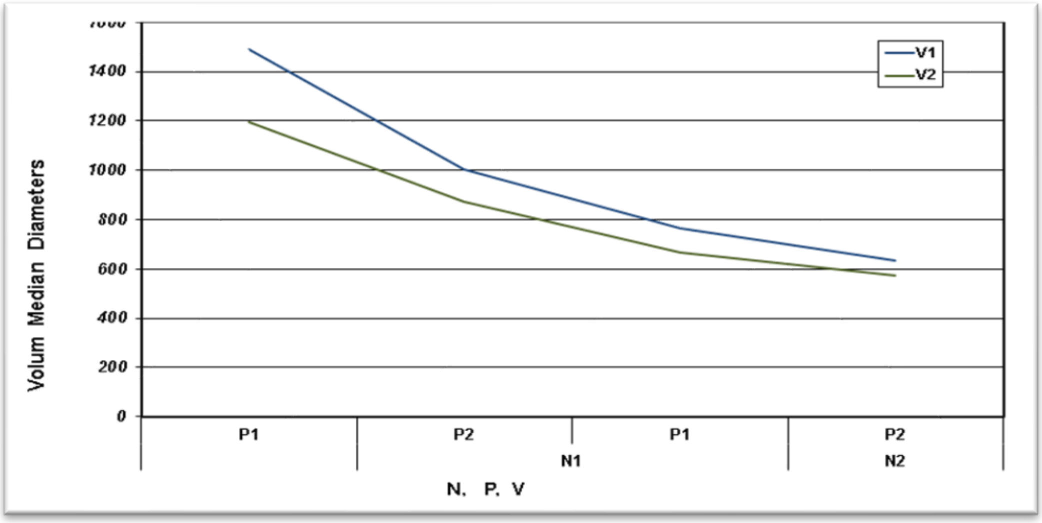


Figure 5. Effect of nozzle type, pressure, spray speed, and their interactions on volume median diameter (VMD).

Spray Coverage (%)

The statistical analysis results, presented in Table (2), indicate a significant effect of nozzle type, spray pressure, spray speed, and their interactions on spray coverage. The AP 120-03C nozzle achieved an average spray coverage of 45.21%, whereas the APS80R 03C nozzle resulted in a lower coverage of 32.36%, measured over a 2 cm² area of water-sensitive paper (WSP). These results suggest that nozzle -producing small spray droplets provide high coverage than those that produce large droplets, which match the results of Carroll (2017).

For the effect of spray pressure on this parameter, high pressure (5 bars) resulted in average spray coverage of 42.16%, while low pressure (3.5 bars) achieved 35.41% coverage. This indicates that the spray pressure affects the percentage of small droplets coverage on the plant canopy. High pressure produces small droplets, which increases spray coverage, while low pressure produces large droplets, which reduces coverage. These findings are consistent with previous research Cooley et al., (2012).

Effect of the spray speed on spray coverage, as mentioned in table (2), statistical analysis indicated a significant effect by increasing the speed from 1.54 km/h to 2 km/h, the spray coverage increased from 36.78% to reach 40.79%, This means the faster the sprays are, the smaller the drops produced, the better the coverage will be, although it should be ensured that the drop size does not fall below 150 microns to avoid drift. These results are consistent with previous findings (Cieniawska, Pentos, 2021).

The results indicate significant two -way interaction between nozzle types and spray pressure on the spray coverage percentage. In 5 bars the AP 120-03C nozzle achieved the highest coverage, which was on average 47.83%, while in 3.5 bars the APS80R 03C nozzle was 36.49% coverage. Similarly, for interaction between nozzle type and spray speed, AP 120-03C nozzle gave 46.86%coverage at 2 km/h, which highlights the direct influence of pressure, speed and direct effect on the spray cover. These findings align with those reported by Alheidary (2019). In addition, a three-way interaction between nozzle type, spray pressure and spray speed showed a significant impact on spray coverage, with the AP 120-03C nozzle at 5 bar and 2 km/h achieving the highest spray coverage of 49.15%.

Table 2. Effect of nozzle type, pressure, spray speed, and their interactions on spray Coverage (%)

N Type of Nozzle	P Pressure (bar)	Speed V km/hr 1.54	2	N*P	Average-N
APS80R 03C	3.5	25.29	31.17	28.23	32.36
	5	34.72	38.25	36.49	
AP120-03C	3.5	40.62	44.57	42.59	45.21
	5	46.51	49.15	47.83	
Value of LSD		LSD: N xP x V= 5.154*		LSD:	LSD:N=1.577*
NxV		Interaction between speed and nozzle type			-----
N1		30.01	34.71	LSD: NxV=3.50*	
N2		43.56	46.86		
VxP		Interaction between pressure and		Average –P	
P1		32.95	37.87	35.41	
P2		40.61	43.70	42.16	
Value of LSD		LSD: P*V= 3.50 * *		LSD:P= *	
Average-V	----	36.78	40.79		
Value of LSD		LSD: V = 1.577 *			

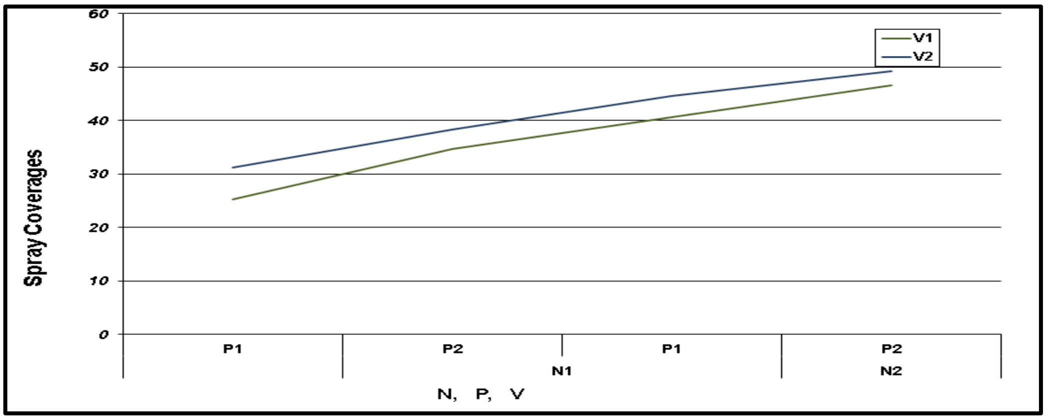


Figure 6. The effect of nozzle type, pressure, spray speed, and their interactions on spray coverage (%).

Number of Drift-Prone Droplets

The results show a significant influence of nozzle type, spray pressure, spray speed, and their interactions on the number of drift-prone droplets (Table (3)). The AP 120-03C nozzle had the lowest number of drift-prone droplets at 34.25, while APS80R 03C nozzle produced 137.33 drift-prone droplets on average. The reason for this difference in droplet count is due to the spray angle (spray coverage width). Wider spray angles mean more spread on the liquid sheet and therefore smaller droplets in general; opposite is for narrow spray angles generating heavy droplets that will run off very easily washing out 90% of the pesticide. These results agree with studies done before (Matthews, et al., 2014).

With respect to the impact of spray pressure on the total amount of drift-prone droplets, a higher pressure (5 bar) yielded fewer drift-prone droplets (an average of 55.58 droplets), and a lower spray pressure (3.5 bar) generated 116 drift-prone droplets. Higher spray pressure means that smaller droplets adhere well to the leaves — unless they drop below the 150-micron mark (which is more prone to drift). These results are consistent with Cooley (2012). Spray speed also significantly impacted drift, with the increased speed (2 km/h) generating fewer drift-prone droplets at an average of 79.42 droplets. This means that at 2 km/h, the droplets were still above 150 microns and therefore less likely to drift. These findings align with the work of Loux, et al., (2013).

For the nozzle type by spray pressure interaction, the AP 120-03C nozzle at 3.5 bar and 5 bar resulted in an average of 18 and 50 drift-prone droplets, respectively. At similar pressures, the APS80R 03C nozzle generated comparatively larger numbers of drift-prone droplets, with 213.67 at 3.5 bar and 61 at 5 bar. These also indicated that the very fine droplets, produced by AP 120-03C on higher-pressure (5 bar) operation, were susceptible to drift due to their low weight, resulting in greater pesticide loss. These results agree with Matthews, et al., (2014) findings.

The two-way interaction between nozzle type and spray speed, the AP 120-03C nozzle at 1.54 km/h produced the lowest number of drift-prone droplets, averaging 32 droplets, while at 2 km/h, it resulted in 36.50 droplets. For the APS80R 03C nozzle, the number of drift-prone droplets was significantly higher, averaging 152.33 droplets at 1.54 km/h and 122.33 droplets at 2 km/h. These results indicate that at higher spray speeds, the AP 120-03C nozzle produced a finer droplet spectrum, suggesting that drift can be reduced by selecting a higher spraying speed, which improves droplet adhesion to the target surface.

The two-way interaction between the nozzle type and spray speed, the fewest average number of drift-prone droplets (observed average about 32 droplets) produced, for AP 120-03C nozzle, at 1.54 km/h and at the 2 km/h spray, the average number of drift-prone droplets was 36.50. The APS80R 03C nozzle also yielded many more drift-vulnerable droplets, with an average of 152.33 droplets at a spraying speed of 1.54 km/h and 122.33 droplets at 2 km/h, which further reveals that in higher speeds, the droplet spectrum produced by AP 120-03C nozzle was thinner, and thus, can lessen drift occurrence, with higher spraying speed providing better attachment of the particles to the target surface.

Table 3. Effect of nozzle type, pressure, spray speed, and their interactions on Number of Drift-Prone Droplets.

N Type of Nozzle	P Pressure (bar)	Speed V km/hr		N*P	Average-N
		1.54	2		
APS80R 03C	3.5	235.00	192.33	213.67	137.33
	5	69.67	52.33	61.00	
AP120-03C	3.5	21.67	15.00	18.33	34.25
	5	42.33	58.00	50.17	
value LSD		LSD: NxPxV = 22.28 *		LSD:N×P=18.76	LSD: N=
NxV		Interaction between speed and nozzle type			-----
N1		152.33	122.33	LSD: NxV=3.50*	
N2		32.00	36.50		
VxP		Interaction between pressure and		Average –P	
P1		128.33	103.67	116.00	
P2		56.00	55.17	55.58	
Value of LSD		* LSD: P*V =18.76 *		LSD: P = 6.141 *	
Average-V	----	92.16	79.42		
Value of LSD		LSD: V = 6.141 *			

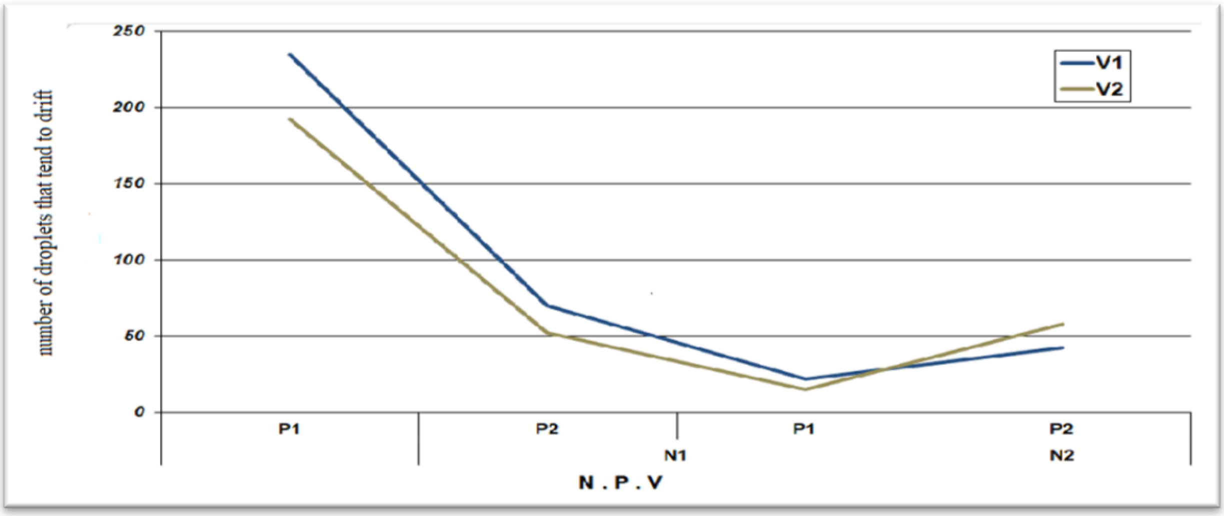


Figure 7. The effect of nozzle type, pressure, spray speed, and their interactions on Number of Drift-Prone Droplets.

Conclusions

The findings show that the AP 120-03C nozzle produces the optimal droplet size and sufficient coverage under a pressure of 3.5–5 bar and spray speed of 1.54–2 km/h, while a higher pressure of 5 bar and speed of 2 km/h generates more drift-prone droplets, resulting in lower field efficacy. Likewise, APS80R 03C nozzle preserve the droplet size uniformly as well as an efficient coverage but also fewer number of driftable droplets at a similar pressure (3.5-5 bar) and speed (1.54-2 km/h) was found to have potential in reducing loss of pesticide and improving efficiency of pest management.

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