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Effects of position angles in twin-jet spray applications on droplet penetration of hydraulic nozzles

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Abstract: This study was conducted to determine the effects of different position angles in twin-jet spray applications on droplet penetration of different nozzle types. Seven different nozzle types (standard flat fan, ST; narrow flat fan, STN; multirange, LU; low-drift potential, AD; air-induction, IDK; twin-jet air-induction, IDKT) were used and nozzles were positioned +15° along the forward direction, perpendicular to ground surface 0° and reverse direction of forward –15°. Spray experiments at 100 L/ha constant application volume were conducted under controlled conditions of a closed facility. Water sensitive paper (WSP) was used as sampling surface. WSP samples were placed vertically and horizontally over both the metal frames and root collar of artificial plants. The present findings revealed that transport potential of spray droplets was quite lower on vertical planes than on horizontal planes. The greatest coverage was achieved with ST, STN, LU, and SC-type nozzles producing fine droplets. Compared to open targets, the coverage ratios around the root collars were quite low and insufficient. In all spray treatments, coverage ratio on the vertical planes was 86.1% lower than the coverage ratio on the horizontal plane. In other words, coverage ratio on the horizontal plane was 7.2 times greater than the coverage ratio on the vertical plane. Transfer efficiency of medium and coarse droplet-producing nozzles to root collars was greater than the transfer efficiency of fine droplet-producing nozzles. Such a ratio for AD, IDKT, and IDK-type nozzles was determined as 37.06, 37.85, and 41.02% respectively. According to the present findings, effects of nozzle position angle on droplet penetration were not found to be significant. However, nozzle position angle along the forward direction increased coverage ratios on the vertical planes.

Key words: Flat fan nozzle, pesticide application, spray coverage, spray simulator, water sensitive paper

1. Introduction

The primary targets in pest and disease control practices include proper transport of active ingredient into target object, well absorption on target object, reduction of drift and providing the greatest biological efficiency with the recommended dose of application. Success in pesticide applications largely depends on proper selection of spray equipment and utilization of selected equipment at optimum operational parameters (Hewitt, 1997; Sayıncı and Bastaban, 2011a).

Hydraulic nozzles used in pesticide applications deliver the liquid spray to target object in droplets at different sizes and speeds (Lefebvre, 1989). There are several factors altering the trajectory of droplets transferred to target object. Therefore, it is quite important to check the volumetric distributions in spray applications (Butler Ellis et al., 1997). Spray angle, spray patters, droplet diameter, spray height, operational pressure, nozzle position angle, and forward travel speed influence volumetric distribution uniformity, are all factors that are considered as controllable internal factors (Stafford, 2000).

Spray characteristics of hydraulic nozzles used in pesticide applications are generally characterized as fine, medium, and coarse droplets, and droplet spectrum is largely influenced by spray pressure (Sayıncı et al., 2013). Differences in spray characteristics of hydraulic nozzles influence transfer energy of droplets to the target object, drift levels, and terminal speeds, thus alter transfer potential and penetration of droplets into target objects (Sayıncı, 2016; Sayıncı et al., 2019b).

The forward speed has an important effect on the transfer of the droplets to the target. Drop distribution uniformity increases when spraying at high forward speed with spray nozzles producing medium and coarse droplets. However, it is recommended to reduce the forward speed when using small orifice size nozzles. In addition, the spray height should be reduced within the allowed limits in terms of drop distribution uniformity (Sayıncı et al., 2020).

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The position angle in spray nozzles has the effect of improving the volumetric distribution uniformity under stationary conditions (Lardoux et al., 2007; Foqué and Nuyttens, 2011). While the position angle of the hydraulic nozzles varies between 0° and 30°, the full cone nozzles can be adjusted between 30° and 45° (Azimi et al., 1985; Srivastava et al., 1993).

Early diagnosis is essential in efficient and sustainable control of pests and diseases. Besides, in chemical applications, transfer of active ingredient directly to the section in which pests and diseases are encountered is also an important issue to achieve high biological efficiency. Greasy cutworm (*Agrotis* spp.) and russet mite (*Aculuslycopersici* Massee)-like pests in vegetables, root crown rot (*Phytophthora capsici* Leon), white rot (*Sclerotinia sclerotiorum* Lib), stem necrosis (*Pseudomonas corrugata*), and grey mold (*Botrytis cinerea* Pers) diseases in vegetables are usually encountered over the forefronts of plant surfaces and crown sections of the plants (Republic of Turkey Ministry of Agriculture and Forestry, 2008). To control these pests and diseases, chemicals are applied to target surfaces through spray droplets. Therefore, spray systems and operational conditions should be selected based on the region of infection (leaf beneath, crown, plant stem, newly developing leaves, etc.) to achieve optimum transfer and penetration into target objects.

In terms of spray characteristics, medium and coarse droplets have greater kinetic energy, spraying distance, and terminal velocity than the fine droplets (Sayıncı, 2016). Thus, they can be transferred to further distances and reach regions of plant canopy close to soil surface at greater quantities (Zhu et al., 2002, 2004). Besides droplet accumulation over the target surface, limited information is available about horizontal or vertical transfer of droplets. For pests and diseases seen over the plant stems or root collar regions, vertical transfer of spray droplets is quite a significant issue.

This study was conducted to investigate i) droplet transfer efficiency of twin-jet hydraulic nozzles at both horizontal and vertical planes; ii) effects of different position angles on spray boom on droplet penetration of twin-jet hydraulic nozzles; iii) to put forth differences of experimental treatments from conventional spraying methods.

2. Materials and methods

2.1. Nozzle types

Seven different flat fan nozzle types (air-induction, IDK; multirange, LU; twin-jet air-induction, IDKT; low-drift potential, AD; standard flat fan, ST; standard narrow flat fan, STN; standard multijet, SC) were used in spraying applications. In IDK, LU, IDKT, AD, ST, and STN-type nozzles, double-flow applications were performed using twin spray caps. In each twin spray cap, same type of 2 nozzles were used. For single-flow applications, SC-type nozzles with multijet spray caps were used. Nozzles were poisoned at 3 different angles in each spray application. The position of the spray boom was altered for this process. Position angles were arranged as: +15° along the forward direction, parallel to the vertical plane at 0°, reverse of the forward direction at −15° (Figure 1).

In spray experiments, forward speeds were altered to operate nozzles with different discharges at constant spray volumes. Forward speed was determined with the use of Equation (1) (Sayıncı et al., 2020).

$$V = \frac{q \cdot \mathrm{n} \cdot 600}{B \cdot N} \quad (1)$$

V: Forward speed (km/h),
q : Nozzle discharge (L/min at 200 kPa),
n : Number of nozzles per spray cap,
B : Nozzle distance (0.5 m),
N: Application volume (100 L/ha).

Nozzle types and operational parameters are provided in Table 1. The 50-mesh cylindrical-type screens were used to prevent clogging (Sayıncı, 2014, 2015, 2016).

2.2. Spray simulator

A linear-motion spray simulator was used in spray applications (Figure 2). Simulator slides were composed of circular cross-section induction bars mounted over 2 industrial profiles (90 × 180 mm). Simulator installation can move linearly over the slides for 12 m and 1000 W servo motor (Delta ASDA-B2, Taiwan) power supply was mounted over the frame structure. A belt and pulley mechanism with a transmission ratio of 1/2.5 was used for motion transmission. Motion control of the vehicle was achieved with the aid of a personal computer connected to servo motor drive. Vehicle forward speed was adjusted through altering rpm of motor shaft. Motor shaft rpm varies between 1 rpm and 5000 rpm, and simulator speed can be controlled within a large range (0.28–12.00 m/s). The spray boom of the simulator is 2.2 m long, and spray height is adjusted mechanically. Over the spray boom, there are 6 nozzle bodies with 3 outlets mounted at 50 cm spacing.

A field sprayer (TP600 Piton Taral, TR) with a 600-L polyethylene tank was used in spray experiments. Piston-membrane type sprayer pump (TAR30, double piston, 40 kg/cm^2 nominal pressure, 30 L/min nominal discharge, 67% efficiency, Taral, TR) was used, and pump shaft was operated at 600 rpm with a redactor-type electric motor (MSD 90L2, 2780 rpm, Gamak, TR). Municipal tap water was used in spray applications.

2.3. Method of sampling

Experiments were conducted in a closed facility with an indoor temperature of 21.2–21.3 °C and relative humidity of 37%–38%.

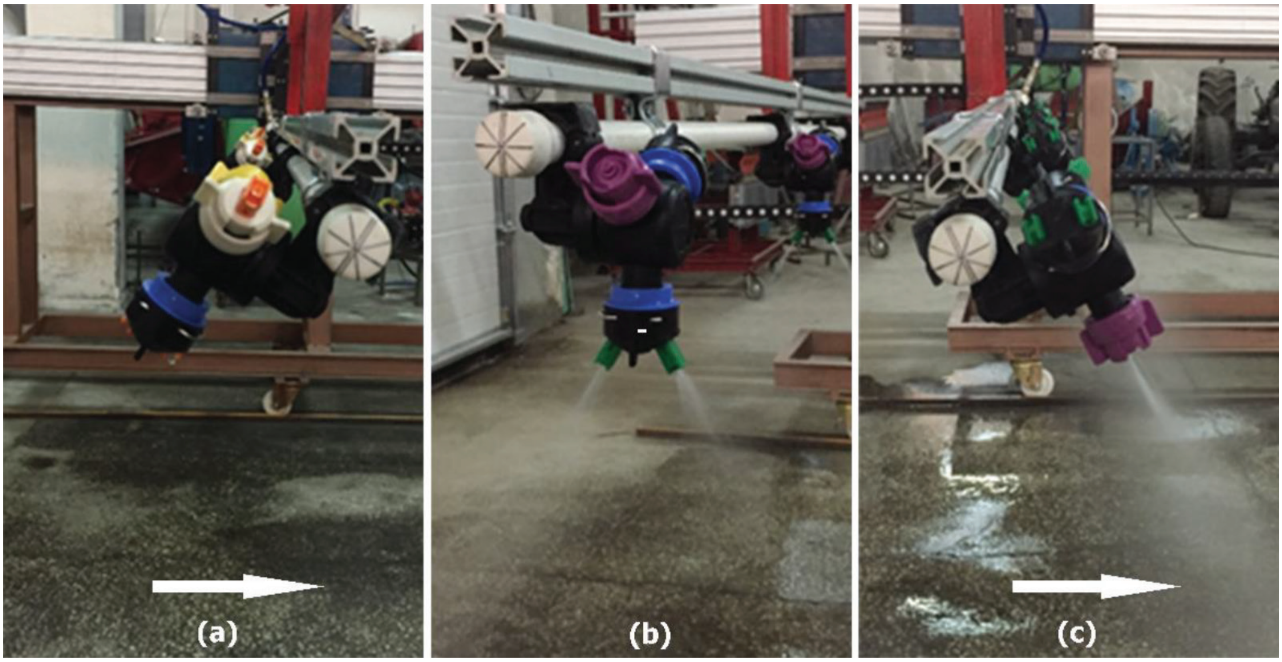
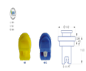


Figure 1. Nozzle position angles on spray boom (a) nozzle position angle: –15°; reverse direction of forward, (b) nozzle position angle: 0°; perpendicular to the horizontal plane, (c) nozzle position angle: +15°; along the forward direction.

Table 1. Nozzle types and operational parameters.

	IDK 120015	LU 120015	IDKT 120015	AD 11002	ST 110015	STN 80015	SC 120025
							
Spray characteristics	Coarse (C)	Fine (F)	Ext. coarse (EC)	Medium (M)	Fine (F)	Fine (F)	Fine (F)
Number of nozzles per spray cap	2	2	2	2	2	2	1
Spray height (cm)	40	40	40	40	40	70	40
Total nozzle discharge rate (L/min)	0.97	0.97	0.97	1.29	0.97	0.97	0.81
Operational pressure (kPa)	200	200	200	200	200	200	200
Application volume (L/ha)	100	100	100	100	100	100	100
Forward speed (m/s)	3.2	3.2	3.2	4.3	3.2	3.2	2.7

*: IDK: air induction (POM, Lechler, DE); LU: multirange (POM, Lechler, DE); IDKT: low-drift potential (POM, Lechler, DE); AD: ; low-drift potential (Ceramic, Albuz, FR); ST: standard flat fan (POM, Lechler, DE); STN: standard narrow flat fan (POM, Lechler, DE); SC: standard multijet (POM, Lechler, DE).

Water-sensitive paper (WSP, 26 × 76 mm Novartis, Syngenta Crop Protection, Basel, CH) was used in the sampling process. The method of sampling is presented in detail in Figure 3. For sampling, 40 cm-high frames were used. The WSP samples were placed at 2 different locations, namely top and bottom, and the samples were positioned at horizontal and vertical planes in each location. For vertical WSP samplings, 30 × 30 × 80 mm wooden blocks were used, and papers were placed in front, side, and rear faces of the block. For horizontal samplings, iron sheet plates were used. Samples were fixed into their places with clips. Sampling was also performed within the canopy of artificial plant (canopy diameter = 68 cm, plant height = 56 cm) to compare droplet penetration of spray

Figure 2. Spray simulator.

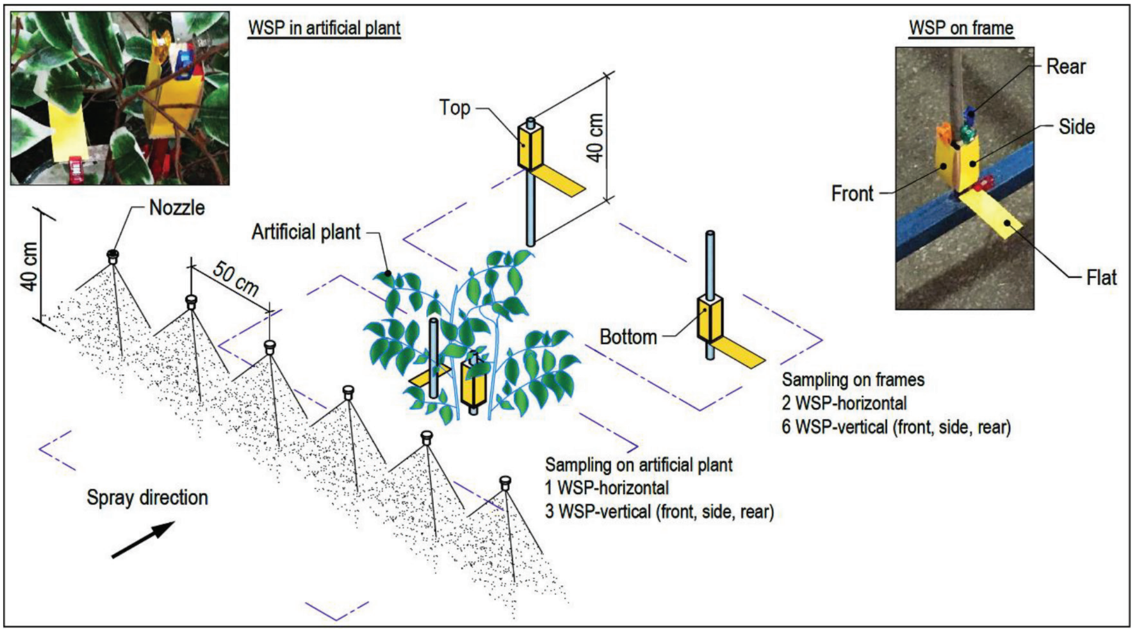


Figure 3. Sampling papers placed within plant canopy and over the frames.

treatments. Plants within sampling space were placed in 3 × 3 groups at 40 × 40 cm (row spacing × on-row plant spacing) spacings. In this arrangement, leaf area index was calculated as 1.84. The WSP samples were placed into plant canopy, 1 at horizontal place and 3 at vertical plane (front, side, rear).

2.4. Surface coverage ratios

Experiments were conducted in 3 replicates. Following the spray applications, dried papers were placed into special covers. Each WSP sample was scanned through a scanner (HP Scanjet 4850, US) at 600 dpi resolution, and the scanned images were saved as image files with a ".jpeg" extension. The WSP images were then converted into gray-tone images with the use of Image-J (Wayne Rasband, National Institutes of Health, USA, Java 1.6.002) software. The threshold (t) values ranging between 0 and 255 to be applied to WSP images were calculated with the use of Equation (2) as specified by Sanchez–Hermosilla and Medina (2004).

$$t = 0.38g + 78.75$$

Mean gray level of images (g) was determined with the aid of a macro module prepared in image processing software. Separate thresholding was performed for each card image, and coverage ratios (%) were determined.

2.5. Statistical analysis

Effects of nozzle types and nozzle position angles on droplet penetration of twin-jet spray treatments were determined with the aid of analysis of variance (ANOVA) in a fully factorial experimental design. Statistical analyses were performed separately for horizontal and vertical sampling planes. Significant means were compared with the aid of Tukey's multiple range test. Statistical analyses were performed with the use of the SPSS 20.0 software (IBM Corporation, Armonk, NY, USA).

3. Results

3.1. Variance analysis results

Effects of sampling locations on droplet transfer to target object were found to be highly significant (Table 2). Present findings revealed that droplets reached the top and bottom sections of the target and root collar sections close to soil surface at different quantities. Surface coverage ratio of the droplets at horizontal plane varied with the type of nozzle. However, effects of nozzle type on surface coverage ratios at vertical plane were not found to be significant. Nozzle position angles did not have significant effects on droplet transfer at horizontal plane. However, nozzle position angle was found to be significant for droplet transfer at vertical plane. In other words, positioning nozzle orifice along the forward direction, perpendicular to ground surface and reverse of forward direction at certain angles, altered the surface coverage ratios at vertical plane.

3.2. Comparison of nozzle types at horizontal and vertical planes

In spray treatment conducted at constant application volume of 100 L/ha, the greatest coverage ratios of droplets transported at horizontal plane were observed in LU, SC, STN, and ST-type nozzles (Table 3). In all nozzle types, quite low spray volumes were observed at vertical plane, and the differences in surface coverage ratios of the nozzles at vertical plane were not found to be significant. Surface coverage ratios were much lower in vertical plane than in horizontal plane. Surface coverage ratio at vertical plane constituted only 13.9% of the coverage at horizontal plane.

3.3. Variations of surface coverage ratios with sampling locations

Considering the sampling locations, at vertical plane, there were significant differences in surface coverage ratios in top section, bottom section, and within plant canopy (Figure 4). At the vertical plane, while the differences in

Table 2. Effects of nozzle types, position angle, and sampling location on droplet transfer at horizontal and vertical planes.

Sampling location	Sources of variation	Degrees of freedom	Mean squares	F	P
Horizontal	Nozzle type (N)	6	308.008	80.311	0.000**
	Position angle (A)	2	6.237	1.626	0.201^{ns}
	Sampling location (L)	2	3149.498	821.210	0.000**
	N × A	12	10.877	2.836	0.002**
	N × L	12	50.911	13.275	0.000**
	A × L	4	16.189	4.221	0.003**
	N × A × L	24	6.618	1.726	0.029*
	Error	126	3.835		
	General	188			
Vertical	Nozzle type (N)	6	5.996	1.273	0.268^{ns}
	Position angle (A)	2	22.570	4.793	0.009**
	Sampling location (L)	2	194.034	41.208	0.000**
	N × A	12	1.929	0.410	0.960^{ns}
	N × L	12	2.371	0.504	0.913^{ns}
	A × L	4	7.978	1.694	0.150^{ns}
	N × A × L	24	2.531	0.538	0.966^{ns}
	Error	504	4.709		
	General	566			

**: P < 0.01 highly significant; *: P < 0.05 significant; ^{ns}: not-significant.

Table 3. Comparison of surface coverage ratios (%) at vertical and horizontal planes.

Nozzle type	Horizontal (mean ± SD)	Vertical (mean ± SD)	Comparison of coverage ratio at vertical plane with the horizontal plane (%)
LU120015	16.59 ± 8.83 a*	1.72 ± 3.14 a*	10.4
SC120025	15.94 ± 7.55 a	1.89 ± 2.11 a	11.9
STN80015	15.86 ± 7.12 a	1.73 ± 2.60 a	10.9
ST110015	15.63 ± 7.55 a	1.71 ± 1.87 a	10.9
AD11002	11.72 ± 4.87 b	2.45 ± 2.43 a	20.9
IDKT120015	9.29 ± 4.17 c	1.68 ± 1.88 a	18.1
IDK120015	8.81 ± 3.86 c	1.88 ± 1.71 a	21.3
General mean	13.40 ± 7.15	1.86 ± 2.30	13.9

*: The means indicated with the same letters (a–d) in the same column are not significantly different according to Tukey's multiple comparison test at a 95% significance level.

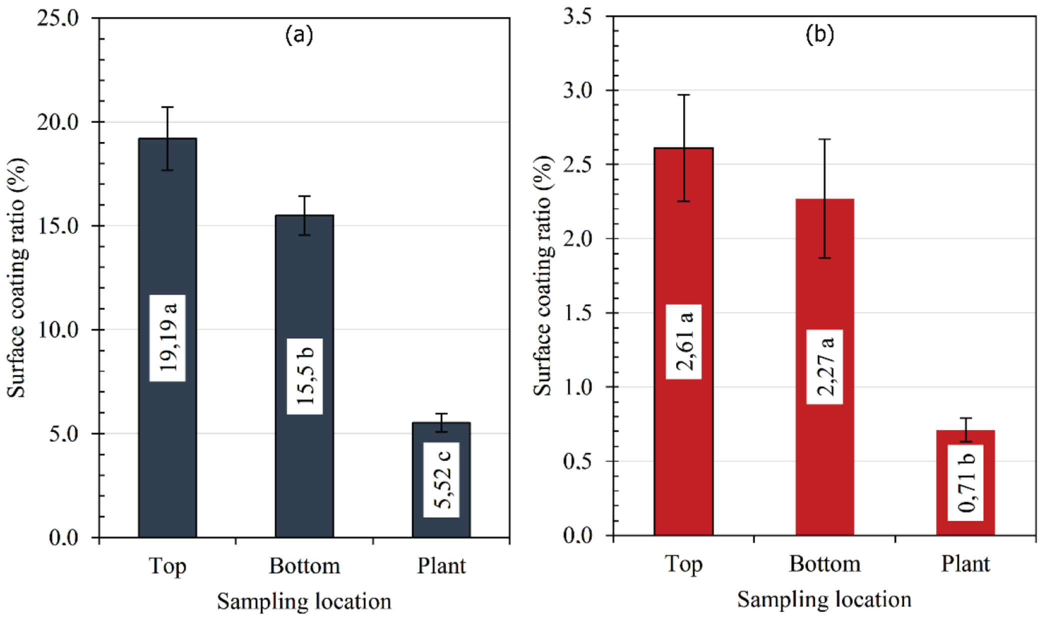


Figure 4. Comparison of surface coverage ratios based on sampling locations (mean ± 2 SE) (means followed by the same letters (a-c) on the bars are not different as determined by the Tukey test at 5% significance level) (a) sampling on horizontal plane, (b) sampling on vertical plane.

surface coverage ratios in the top and bottom sections were not significantly different, a quite small number of droplets were transported to root collar section of the plants.

Average surface coverage ratios of droplets that reached all the sampling surfaces are presented in Figure 5. The greatest coverage was achieved at the horizontal plane. The droplets transported at vertical plane yielded the greatest coverage at "forefront" along the forward direction and yielded quite low coverage ratios at "side" and "rear" surfaces.

3.4. Variation of surface coverage ratios with nozzle position angles

As detailed in Figure 6, the effects of nozzle position angles on surface coverage ratios at horizontal plane were not found to be significant. However, the nozzle position angle arranged along the direction of forward movement significantly increased droplet transfer potential on vertical forefront surfaces.

3.5. Comparison of droplet penetration of nozzle types

Coverage ratios of droplets were greater at the bottom

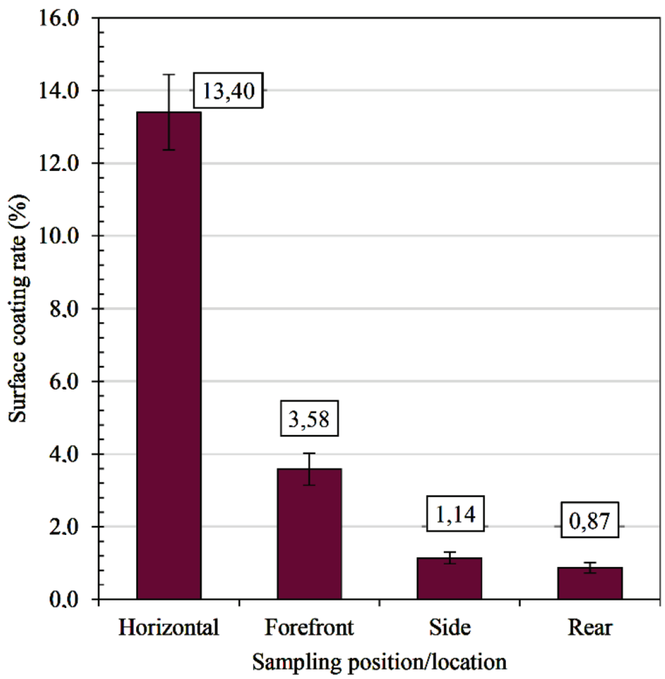


Figure 5. Comparison of surface coverage ratios based on sampling surfaces (mean ± 2 SE).

sections compared to the root collar section (Figure 7). Thus, quite a low number of droplets reached the root collars. The percentages presented on horizontal axis of the figure show the reductions in coverage ratios on root collars as compared to the bottom section.

4. Discussion

4.1. Surface coverage ratios (%) of nozzles at horizontal and vertical planes (%)

Homogeneous distribution and coverage of droplets over the target surface is the primary concern in spray applications. Although all nozzles used in this study had flat fan spray geometry, they all had different designs, thus had different droplet characteristics. Therefore, at the same volume of application, while coarse droplets may yield low coverage ratios, fine droplets may yield greater coverage ratios (Sayıncı and Bastaban, 2011b). Considering the droplet transfer, despite different bean angles of nozzles used in standard spray applications, droplets mostly transported to horizontal surfaces. In the present study, coverage ratios were also greater on horizontal surfaces than the vertical surfaces. Twin-jet applications and nozzle types did not have significant effects on droplet transport to vertical forefront surfaces. According to this finding, the nozzle position angle may have reduced the kinetic energy of the droplets.

Nozzle types used in the present study were divided into 3 categories based on spray characteristics: LU, SC, STN, and ST-type nozzles produce fine droplets (Lechler, 2018)[1]; AD-type nozzles produce medium droplets (Albuz, 2017)[2]; and IDKT and IDK-type nozzles produce coarse droplets (Lechler, 2018)[1]. Theoretically, at the same volume of application, fine droplets are generally expected to yield greater coverage ratios than the medium and coarse droplets (Sayıncı and Bastaban, 2011b). Thus, the present findings revealed the same outcomes. However, the sole effect of nozzle types on pests and diseases over the plant stems or root collar regions was not found to be significant. The results of the research conducted by Sharpeet al. (2017) confirmed this finding. Such a case was considered as an important problem in pest control over these critical sections of the plant.

4.2. Surface coverage ratios (%) of droplets transported to sampling locations

Uniform sprays are desired in spray applications. Such a case yields homogeneous transport of active ingredients to target objects. However, sampling locations also play a great role in droplet transfer to target objects. Pests and diseases may be encountered beneath the leaves, over the leaves, on leaf petioles, upper sections from where new shoots are emerged, bottom sections of the plant, or around the root collars close to soil surface. In this sense,

[1] Lechler (2018). Agricultural Spray Nozzles, 2018 US Catalog [online]. http://www.lechler.de [accessed 10 April 2018].

[2] Albuz (2017). Spray Nozzles. Albuz Catalog [online]. Website http://albuz-spray.com [accessed 01 April 2019].

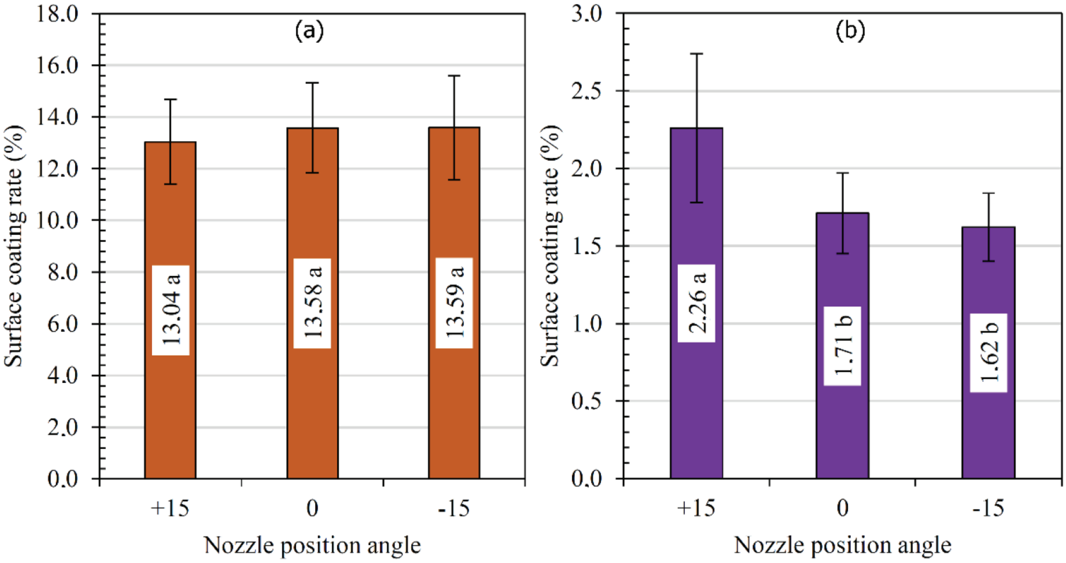


Figure 6. Comparison of surface coverage ratios based on nozzle position angles (mean ± 2 SE) (means followed by the same letters (a-b) on the bars are not different as determined by the Tukey test at 5% significance level) (a) surface coverage on horizontal plane, (b) surface coverage on vertical plane.

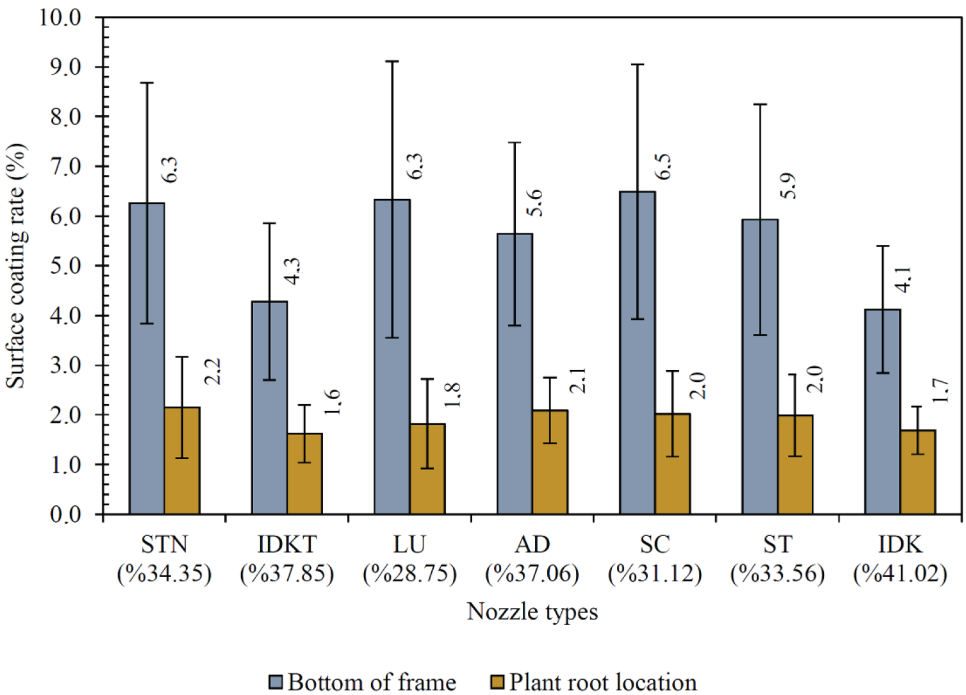


Figure 7. Comparison of droplet penetration of nozzle types (mean ± 2 SE).

transfer of chemicals directly to the plant sections where the pests and diseases were encountered may significantly improve biological efficiency. However, according to the present findings on surface coverage ratios, quite low droplet penetration into plant canopy was observed. Such a finding complies with the results of Sayıncı et al. (2019a) indicating quite a low droplet transfer to root collar section.

To compare different nozzle types, WSP surfaces were placed at horizontal and vertical planes in top and bottom sections of the plants. Droplet transfer potentials were quite weak at vertical plane. On the other hand, droplets yielded greater coverage ratios at top sections close to nozzle orifice. When the vertical forefronts were assessed separately, it was observed that droplets mostly reached the forefront surfaces along the forward direction, and that quite a smaller number of droplets reached side and rear surfaces. Such a case indicates the risk to be taken in control of pests and diseases around the root collars.

4.3. Effects of nozzle position angle on surface coverage ratio

Position angles of hydraulic nozzles are reported as between 0 and 30º (Azimi et al., 1985). Nozzle position angle allows droplets to spray at a larger beam and increases coverage ratios at certain heights and improves distribution uniformity. However, while improving volumetric distribution uniformity, it reduces droplet discharge speeds from the orifice and therefore results in low penetrations (Azimi et al., 1985). There are a limited number of studies about this issue under field conditions in which environmental factors play a great role. Zhu et al. (2002) positioned standard nozzles at 0–15º angles in peanut spray and indicated that the position angle did not alter droplet penetration. Sayıncı et al. (2019a) reported that in standard spray applications, only 25% of droplets reached the stems and root collars of plant canopy. In the same study, 40% increase was reported in surface coverage ratios when the nozzles were positioned at 45º angle with the forward direction. It was determined in the present study that 15º position angle in the forward direction increased droplet transfer efficiency to target surfaces and thus increased surface coverage ratios. However, such an increase was at quite low levels in the vertical plane compared to the horizontal plane.

4.4. Comparison of droplet penetrations of nozzle types

Since low volume of droplets reached the bottom section, sufficient coverage was not achieved. Since the sampling surfaces at bottom section are open targets, plant canopy diameter, plant height, and leaf area index-like plant characteristics have significant effects on droplet transfer potentials. In terms of the effects of plant characteristics on droplet penetration, Zhu et al. (2002) indicated greater significance of leaf area index and plant height than leaf density. Although STN, LU, SC, and ST-type nozzles producing fine-textured droplets yielded high coverage ratios, some of the droplets are exposed to drift in application conducted under windy conditions. Sayıncı (2016) indicated that since fine droplets had smaller terminal velocity and kinetic energy, they are more prone to drift. Zhu et al. (2004) reported the lowest transfer to plant bottom sections in spray applications to peanut plants under open field conditions for standard flat fan nozzles producing fine droplets. In this case, since medium and coarse droplets produced by AD, IDKT, and IDK-type nozzles are resistant to drift, current coverage ratios can be sustained. Thus, when the coverage ratios at root collar sections were compared with the coverage ratios at bottom sections, it was observed that droplet transfer potentials were ordered as IDK > IDKT > AD > STN > ST > SC > LU-type nozzles with droplet transfer efficiencies of 41.0, 37.9, 37.1, 34.3, 33.6, 31.1, and 28.8%, respectively.

In the present study, standard multijet flat fan nozzles (SC) yielded similar spray characteristics with twin-jet applications. In this sense, coverage ratio and droplet penetration of SC-type nozzles were found to be equivalent to the performance of twin-jet nozzle types producing fine droplets.

5. Conclusion

The present findings revealed that there is a further need for pesticide application equipment as an alternative of hydraulic nozzles or to support droplet transfer process of hydraulic nozzles for better control and management of pests and diseases encountered around the root collars or over the lower sections of plant stems. In case of preference of hydraulic nozzles in spray applications, application volumes should be increased based on plant characteristics. In the present study, positioning nozzles at a certain angle with forward direction increased surface coverage ratios. In terms of droplet penetration, twin-jet spray applications were not found to be different from the standard spray applications. In all spray applications, quite low droplet transfers were observed on vertical forefronts of the target surfaces.

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