EFFECT OF NOZZLE HEIGHT AND TYPE ON SPRAY DENSITY AND DISTRIBUTION FOR A GROUND FIELD SPRAYER

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Abstract. *A field study was conducted to reveal the effect of nozzle type and height on spray density (application rate) and distribution utilizing a ground field boom sprayer. Six nozzle types (four flat fan nozzles numbered from 1 to 4 and two hollow cone nozzles numbered 5 and 6) were tested at four nozzle heights (15, 30, 45 and 60 cm). In addition to the conventional method of employing a spray patternator, water sensitive papers (WSPs) were also utilized as a second means to measure the two characteristics (density and distribution) of the spray application. For all nozzles tested, results revealed that the application rate error and uniformity of distribution (UD) of the spray liquid were proportional to nozzle heights. For instance, increasing the height of the hollow cone nozzle No. 5 from 15 to 60 cm caused an increase in the error in application rate from 10.9% to 47.6% and in the UD from 36.2% to 92.5%. On the average, the application rate for the middle nozzle was observed to increase with increasing nozzle height for all nozzles tested. That was attributed to increasing overlap from side nozzles. The average application rate for the flat fan nozzle No. 2 increased from 358.7 to 474.1 L/ha as the nozzle height increased from 15 to 60 cm. The tested flat fan nozzles exhibited a better spray distribution and lower error in application rate at all nozzle heights compared to the hollow cone nozzles. WSP analysis showed the same general trend revealed by the spray patternator method. WSP analysis showed that the application rate, expressed as a percentage of wetted area (Y), and UD values were proportional to nozzle height. Y and UD for nozzle No. 5 were found to increase from 55.6% to 59.1% and from 50.6% to 84.5%, respectively, as the nozzle height increased from 15 to 60 cm.*

Keywords. *Sprayer, Nozzles, Uniformity, Spray density, Spray distribution, Coefficient of Variation (CV), Water Sensitive Paper (WSP).*

INTRODUCTION

Pesticides have been a very popular means to exterminate agricultural pests. About 350 million kg of pesticides are annually applied on 114 million ha of cropland in the United States of America, resulting in an average deposit of 3.1 kg/ha (Pimentel and Levitan, 1986). In Saudi Arabia, the amount of liquid and powder pesticides imported in 2007 was 6.7 million liters and 2.8 thousand tons, respectively (Ministry of Agriculture, 2008). The efficient application of agricultural chemicals is a major social and economical issue in current agricultural business. Public environmental concerns have increased against the agricultural chemicals, such as pesticides, which are viewed as a major source of environmental pollution. Moreover, the cost of these chemicals has also increased. Inaccurate application of pesticides could result in more contaminated environment and higher farming cost (Al-Gaadi, 1998). Therefore, the accuracy of pesticide applications has to be increased in order to avoid or greatly reduce the bad consequences of applying these chemicals.

It has been found that with commonly used ground boom sprayers, a large portion of spray chemical did not reach the target, and chemicals that reached the intended plant target were often not distributed uniformly (Pimentel and Levitan, 1986). Peterson et al. (1993) reported that the characteristics of the nozzle tip used, such as droplet size, flow rate, spray angle and spray distribution pattern have a great effect on the performance of the spraying system utilized. In addition, boom height (nozzle height) was reported by Bode et al. (1976) to be the most significant variable in the prediction equation for spray drift, where even small increase in the height (from 43 to 58 cm) could cause a major difference in the drift equation outcome, making it a very critical factor in predicting total drift and system accuracy. Smith (1992), Faqiri and Krishnan (2005), Womac et al. (2001), Iyer and Wills (1978), Wang et al. (1995) and Krishnan et al. (1988) studied the uniformity and percent recovery of different nozzle types through both laboratory and field tests. Different spraying pressures, nozzle heights and field ground speeds were used as parameters in the tests. The deposit coefficients of variation (CVs) were found to be affected by all parameters involved in the studies. Smith et al. (2000) developed models to predict spray drift from a ground boom field sprayer. Nozzle height was a factor thought to be strongly related to spray drift deposits. Zhou et al. (1996) developed a computer model to predict the spray angle, being one of the important parameters characterizing a flat fan nozzle for a given nozzle geometry. Height of the boom and nozzle spacing were reported to be directly related to the nozzle spray angle. Jeon et al. (2004) studied the dynamic effects of sprayer boom on application uniformity for different droplet sizes. Instantaneous boom heights of less than 1.5 m maximized spray coverage and minimized variation in coverage for 255 μm (Dv0.5) droplets, however, the height did not significantly affect spray coverage and droplet density for the 588 μm (Dv0.5) droplets. Observed correlations indicated that boom stability is an important element in the uniformity of spray application. Implications are that active sprayer suspensions to stabilize boom movements should improve application uniformity; however, field conditions could limit the possibility of achieving complete uniformity. Womac et al. (1999) stated that the droplet size was a crucial element that could greatly affect the drift of agricultural spray applied in windy conditions. The droplet size was thought to be inversely proportional to the potential off-target drift, given that nozzle height, wind speed and atmospheric conditions were constant. Bache et al. (1988) reported that the droplet size was affected by many factors, such as nozzle design, nominal size, spray discharge angle, liquid flow rate, operating pressure, orifice characteristics and spray liquid characteristics.

Water-sensitive papers (WSPs) are widely utilized by researchers and applicators to measure droplet size and uniformity of agricultural chemicals applications (Hoffmann and Hewitt, 2005). The authors described the WSP as being a sampling method consisting of cards coated with bromoethyl yellow, which became blue as a result of its contact with water drops. They used WSP to compare three imaging systems (USDA-ARS and Swath Kit camera-based systems and DropletScan scanner-based system) in analyzing droplets of an agricultural spray. Results of the imaging systems were found to be comparable. However, the inability of detecting small drops and spreading of drops on the paper, making them larger than actual, could degrade the accuracy and limit the use of the WSP method. Sánchez-Hermosilla and Medina (2004) developed a methodology to improve coverage measurement of agricultural sprays using WSP and image analysis processing. The core of their study was to produce a binary image by setting a gray intensity threshold that could eliminate the ambiguity, attributed to lack of uniformity in contrast between water generated spots and background of the WSP surface, in determining spots on the WSP. A relationship between the intensity threshold required to obtain a binary image and the mean gray level of the image was reached. This relationship could be utilized to select an adaptive threshold with the mean gray level when analyzing WSP samples. Fox et al. (2003) used WSP and an image analysis system to evaluate a sprayer system in nursery trees. A stain size threshold was set to eliminate tiny dots that could result from noise produced by the utilized image analysis system. Uniformity was determined by measuring the area coverage percentage for different WSPs placed at different locations on the target trees. Wolf (2003) utilized WSP to collect data of spray droplets from a ground sprayer for both in-field and downwind droplet deposits. The purpose of his study was to prove the ability of the DropletScan™ software in measuring differences in droplet characteristics, such as percent area coverage, in both deposits.

The overall objective of this research is to investigate, through a field study, the effect of sprayer boom height and nozzle type on the spray density (defined as application rate) and distribution. Water sensitive paper (WSP) method was employed, along with the conventional spray patternator method, to measure the two spray characteristics.

MATERIALS AND METHODS

A field study was conducted, at the College of Food and Agricultural Sciences Research Center in King Saud University, to investigate the effect of nozzle height and type on the dynamic performance of a ground field sprayer in terms of spray liquid distribution uniformity and density. Four different nozzle heights (15, 30, 45 and 60 cm) and six different JACTO™ nozzle types (JMaquinas Agricolas Jacto S.A., Pompēia, SP, Brazil) shown in Figure 1 were incorporated in the study. Given that the pressure of 600 kPa (6 bar), the ground speed of 6 km/h and the nozzle spacing of 50 cm along the sprayer boom were known constant test parameters, a static test was conducted to calibrate each nozzle type for discharge rate and application rate (Table1). This was performed by collecting a certain amount of water directly from the nozzle at a test pump pressure and at 0 cm nozzle height for a specific time period and calibration discharge rate (reference discharge rate) was determined. Using the determined reference discharge rate, the calibration application rate (reference application rate) was calculated using the following formula:

Application rate = discharge rate / (ground speed * nozzle spacing) (1)

Field tests were conducted utilizing a 10-m boom pull type field ground sprayer (Figure 2). A total of 20 nozzles were spaced at 50 cm along the sprayer boom. The boom was made of three segments so it could be folded during transportation or when only part of the boom was desired to be used. Moreover, the boom was designed where its height relative to a collecting table surface could be changed within the range of 15 to 90 cm. The sprayer was equipped with a 1000 L capacity liquid spray tank. A 9.7 kW (13 hp) reciprocating pump operated by the tractor PTO was utilized to withdraw spray liquid from the tank and pressurize it to the nozzles. The pump was rated to generate a pressure of up to 6000 kPa (60 bar) with a flow rate of 85 L/min at a speed of 650 rpm. For the purpose of this study, a segment of the sprayer boom that contained three nozzles was implemented. For each nozzle type and boom height, the field test was conducted by driving the sprayer out in the field at the test ground speed (6 km/h) and pump pressure (600 kPa) over a course of approximately 100 m of asphalt surface, where three operating nozzles passed over a collecting table that was placed in the middle of the traversed test course. This field test was repeated three times and the average water collected was calculated to compose one set of the study data. Considering four nozzle heights and six nozzle types, a total of 24 data sets were produced for the whole study. Water sensitive papers (WSP) with the size of 2.6X50 cm (Syngenta Crop Protection AG, 2007) were utilized in one of the repetitions as a second data collection method. The papers were

Table 1: Specifications of test nozzles.

Nozzle No.	Nozzle type	Nozzle code	Nozzle color	Reference discharge rate (L/h)	Reference application rate (L/ha)
1	Flat fan – low drift	ADI 04	Red	148.0	493.3
2	Flat fan – low drift	ADI 03	Blue	100.8	336.0
3	Flat fan – low drift	ADI 02	Yellow	77.6	258.7
4	Flat fan	AXI 02	Yellow	75.8	252.7
5	Hollow cone	JA-4	Red	107.5	358.3
6	Hollow cone	JA-2	Black	51.7	172.3

Figure 1: Test nozzle types.

Figure 2: Field ground sprayer prepared for the experiment.

numbered and marked so the location of each paper under the nozzles, the nozzle type and height in which they were used would be known. Data of average wind speed and air temperature during field experiments were recorded at 2.8 km/h and 24.7˚c, respectively. A 2.5X1.6 m portable spray pattern table was placed in the sprayer travel course in the orientation shown in Figure 3. The table was fabricated of galvanized metal sheets and used to collect spray liquid (water) from the tested nozzles. The table surface under the nozzles was made of corrugated sheets to form forty receiving channels with 6.2 cm separation distance. Therefore, with a nozzle spacing of 50 cm, each nozzle theoretically covered eight receiving channels. A slight slope was maintained in the corrugated table surface to completely drain the channels into the plastic tubes. A flat area at the rear side of the table was utilized to lay out the WSP in the test repetitions where they were used.

Due to the low volume of collected water in most of the collecting tubes, a sensitive digital scale with an accuracy of ± 0.01 g (Mettler-Toledo GmbH, 2004) was implemented to accurately measure the weight of collected water.

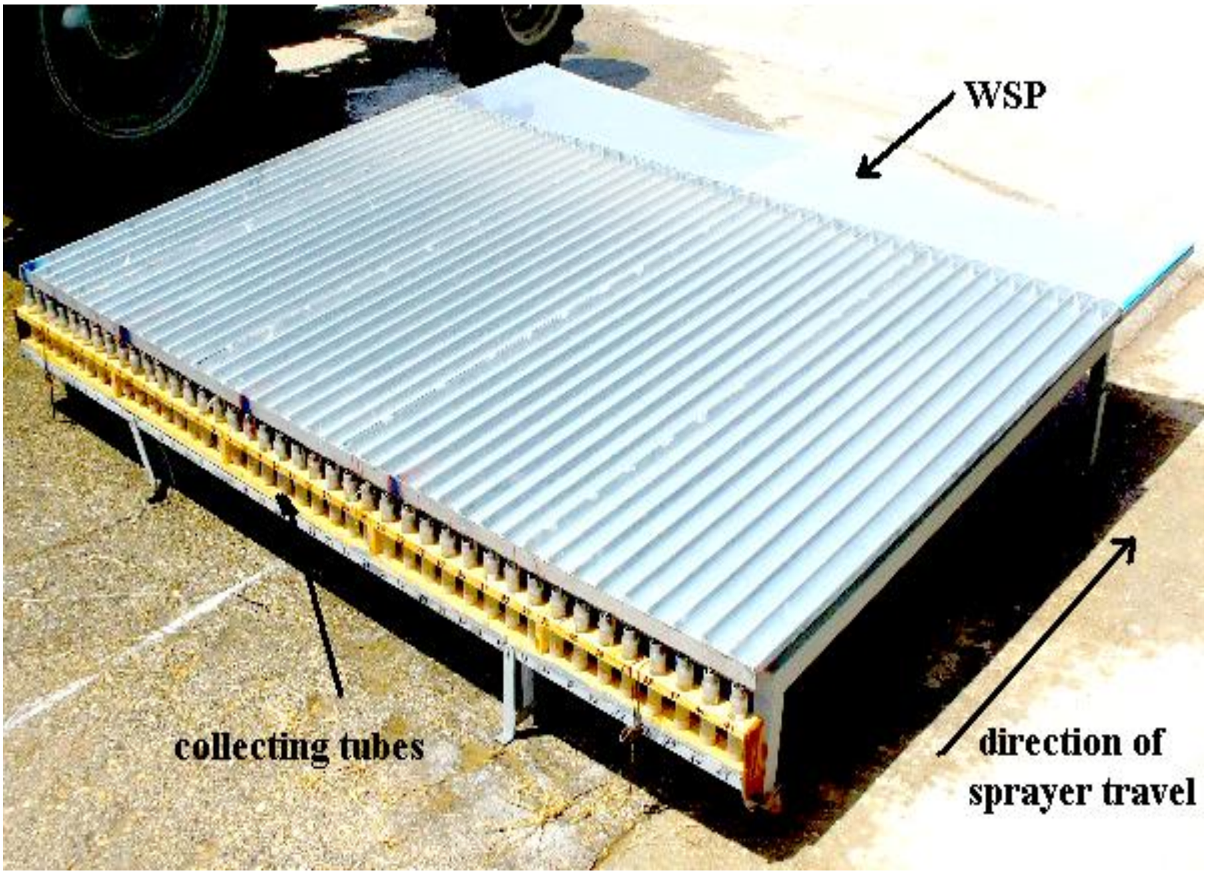


Figure 3: The spray patternator.

RESULTS AND DISCUSSION

The initial raw data of the spray liquid (water) collected in the collecting tubes for each nozzle type at each nozzle height was utilized to illustrate the general spray distribution characteristics. At the lowest nozzle height of 15 cm, it could be clearly seen that, for all test nozzle types, the highest weight (volume) of water was found directly under the nozzles and sharply decreased on both sides of the nozzles producing highly defined peaks and valleys (Figure 4). For example, the weight of water collected directly under the middle nozzle of nozzle No. 1 reached 10 g, however, this weight decreased to approximately 2.5 g on both nozzle sides with overlap from the two side nozzles. To improve uniformity, overlap is very common and required in normal field spraying operations; therefore, the middle nozzle where overlap occurs will be used in this analysis to be more representative of field operations. It can be seen from Figure 4 that the spray liquid at 15 cm nozzle height was stretched over only 28 collecting channels. As the nozzle height increased to 30 cm, the discharge out of the nozzles was distributed on larger area (stretched over 30 collecting channels) producing smoother curves (Figure 5) compared to those produced at 15 cm nozzle height. Figure 6 shows the distribution

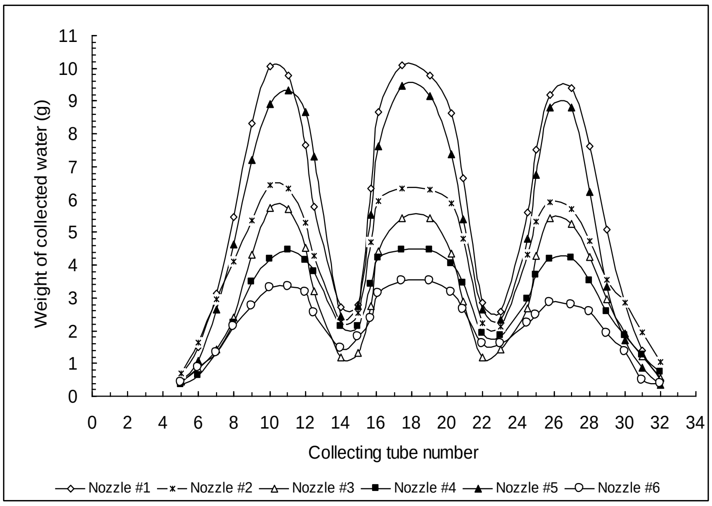


Figure 4: Spray distribution at 15 cm nozzle height.

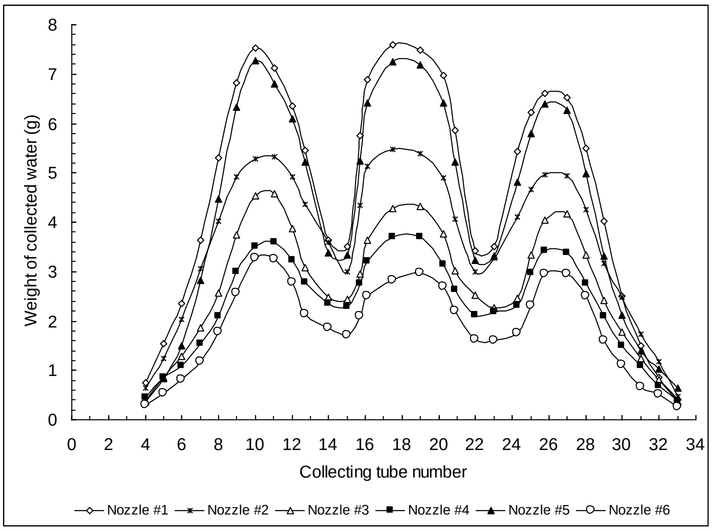


Figure 5: Spray distribution at 30 cm nozzle height.

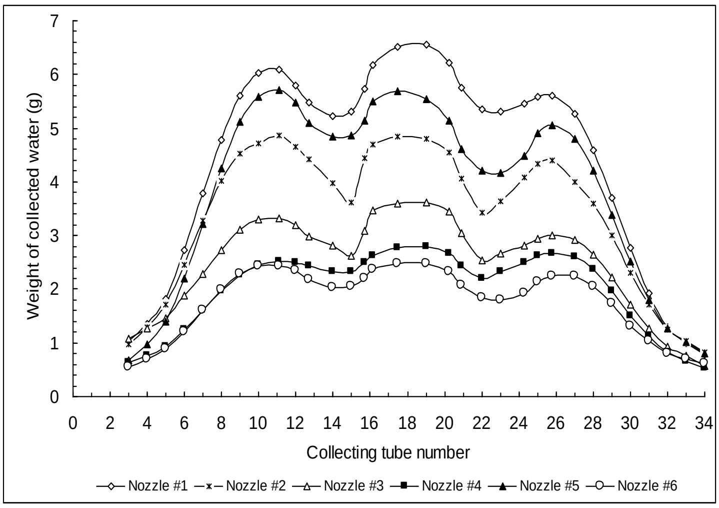


Figure 6: Spray distribution at 45 cm nozzle height.

curves of the nozzles' output at 45 cm nozzle height. At this nozzle height, the nozzles' discharge was applied on more collecting channels (32 channels) and overlap was increased causing reduction in the gaps between peaks and valleys. For example, the weight of water collected directly under the middle nozzle of nozzle No. 1 was 6.5 g, however, this weight decreased to 5.5 g on both nozzle sides with overlap from the two side nozzles. The distribution curves of the nozzles' output were very smooth and almost flat at 60 cm nozzle height as depicted in Figure 7. Nozzles' discharge was applied on more collecting channels (33 channels) and overlap was increased producing almost flat distribution curves for the middle nozzle of all nozzle types. The difference between the highest weight of water of 5.7 g collected under the middle nozzle of nozzle No. 1 and the lowest weight of water of 5.0 g was minimal (only 0.7 g) indicating that the spray liquid was almost evenly distributed on the area covered by this nozzle. The raw data analysis illustrated a general trend which suggested that, for all test nozzle types, the density of the spray liquid was inversely proportional to the nozzle height. However, the spray liquid distribution uniformity was proportional to the nozzle height.

For each nozzle type, the application rates under the middle nozzle at each nozzle height were determined based on the average water collected in the collecting tubes and the area covered. If, for example, the amount of average collected water in a specific tube was 4 gm (4 mL), then the application rate at that location would be calculated by dividing the volume of water collected on the area covered (the area of the receiving channel), which had a width of 6 cm (distance between collecting tubes) and a length of 160 cm (the dimension of the collecting table parallel to the sprayer travel direction). Since each nozzle theoretically covered eight channels, then eight application rates were calculated for the middle nozzle at each nozzle height as shown in Figure 8 for nozzle type No. 1. It can be seen from Figure 8 that the application rate for this nozzle type at a nozzle height of 15 cm reached over 1000 L/ha directly under the nozzle, while it was as low as 280 L/ha on the nozzle sides. As the nozzle height increased to 60 cm, the application rate ranged between 530 and 504 L/ha producing a flat curve indicating high distribution uniformity (93% as shown in Table 2) of the spray applied on the area covered by this nozzle. However, the error in application rate (average application rate compared to reference application rate listed in Table 1) increased with increasing nozzle height, where it increased from 0.9% to 14.4% as the nozzle height increased from 15 to 60 cm (Table 2). Figures 9, 10, 11, 12 and 13 for nozzle type No. 2, 3, 4, 5 and 6, respectively reveal the general trend of the nozzles' application rates and distributions at different nozzle heights. The trend indicated that, for all nozzles tested, the spray distribution uniformity

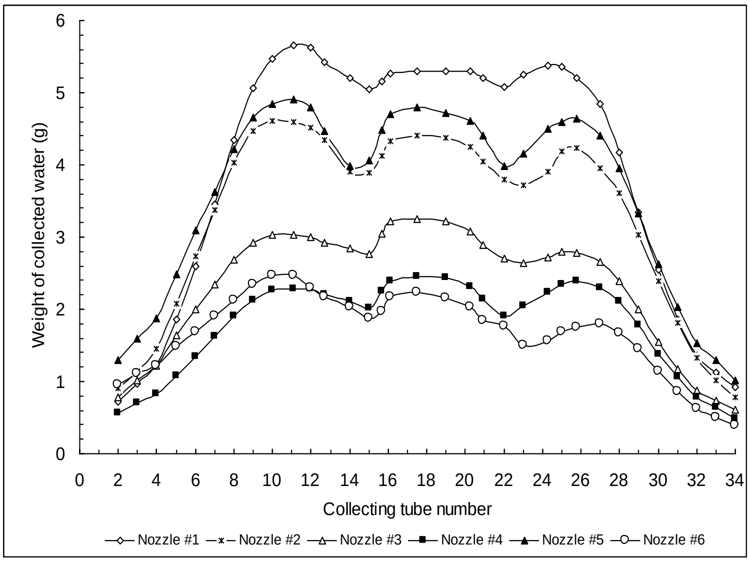


Figure 7: Spray distribution at 60 cm nozzle height.

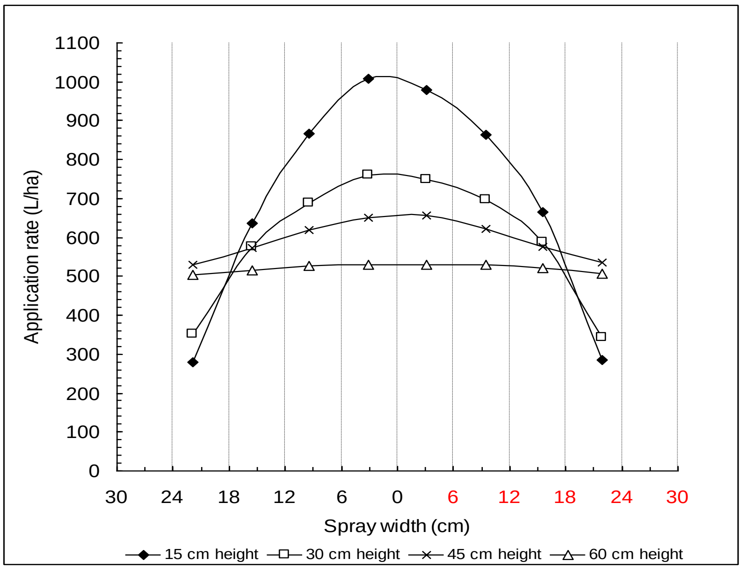


Figure 8: Uniformity of application rate for nozzle No. 1.

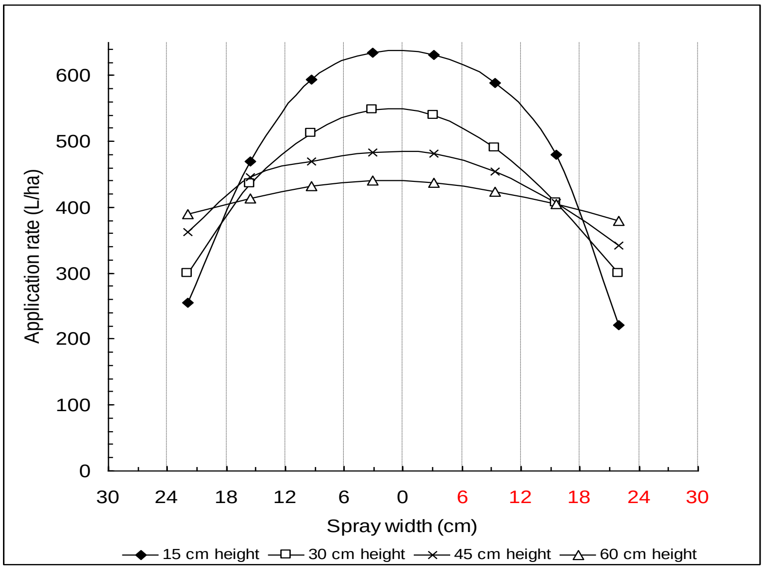


Figure 9: Uniformity of application rate for nozzle No. 2.

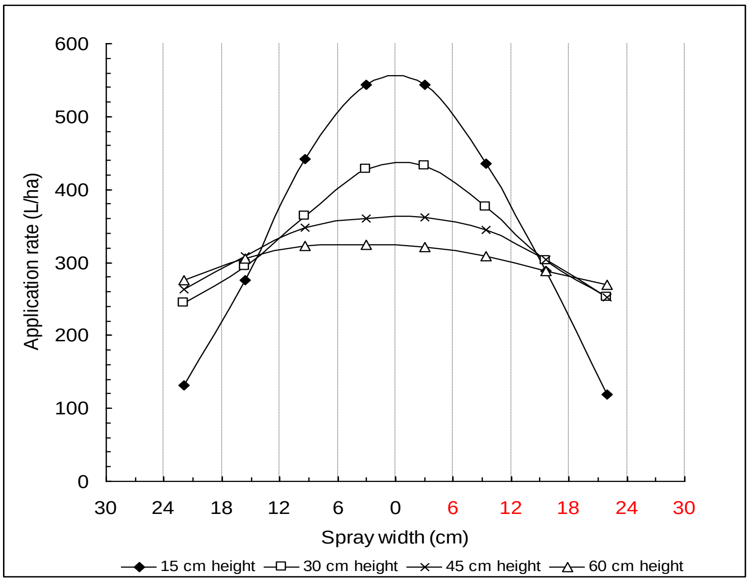


Figure 10: Uniformity of application rate for nozzle No. 3.

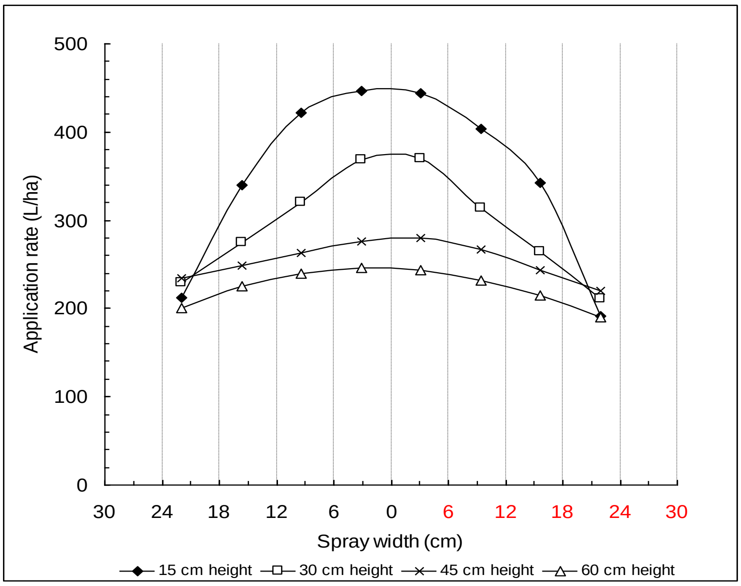


Figure 11: Uniformity of application rate for nozzle No. 4.

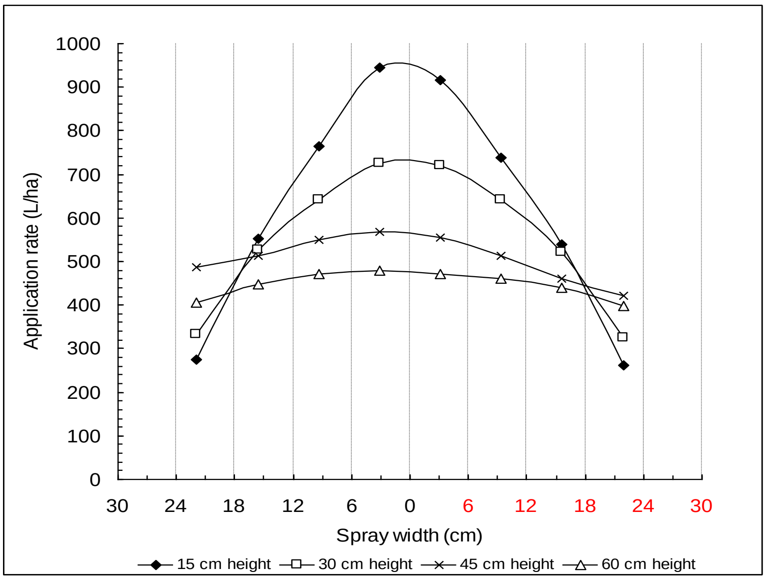


Figure 12: Uniformity of application rate for nozzle No. 5.

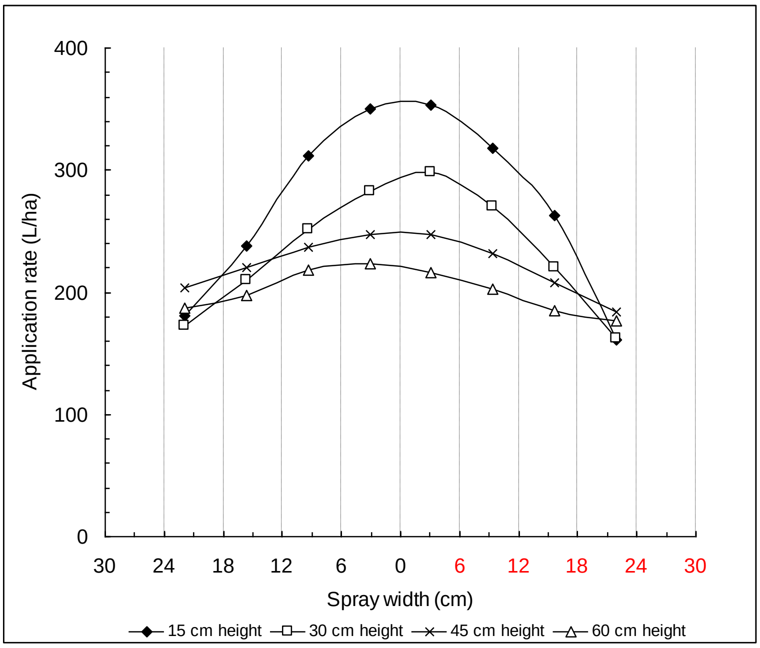


Figure 13: Uniformity of application rate for nozzle No. 6.

and application rate errors were proportional to nozzle height. Therefore, a compromise needs to be made for a specific nozzle in order to maintain adequate distribution uniformity with minimal error in application rate. For example, the nozzle height of 45 cm for nozzle No. 1 produced a good UD of almost 89% with an error in application rate of less than 5% (Table 2). For all nozzles tested, nozzle No. 4 exhibited a good combination of high UD (almost 92%) and low application rate error (1.5%) at a nozzle height of 45 cm (Table 2).

Water sensitive papers (WSPs) were utilized as a second means to reveal the effect of nozzle height and type on spray uniformity and coverage. The WSP under the middle nozzle was selected after the spraying operation and scanned for each nozzle type at each nozzle height. Ten 2x2 cm square samples were taken from each digital scanned WSP image. The colors on WSP were converted into either black for wetted area (originally blue) or white for non-wetted area (originally yellow). This was conducted to remove any colors in between blue and yellow for complete distinction of wetted areas on the scanned WSP. A software program was designed to calculate the percentage of black area (wetted area) in the 2 cm^2 samples. An example of the ten samples is shown in Table 3 for nozzle No. 1 at the four nozzle heights, where the number under each sample represents the percentage of the wetted area. For all nozzle heights, the highest percentages of the wetted area were found in the middle samples (directly under the nozzle), where this percentage was around 90 in samples No. 5 and 6 at 15 cm nozzle height (Table 3). However, this highest percentage of wetted area was found to decrease with increasing nozzle height, where it was measured at around 70 for 60 cm nozzle height.

Table 2: Statistical data of nozzle application rate.

Nozzle No.	Height (cm)	Avg. App. Rate(L/ha)	CV (%)	UD (%)	App. Rate Error (%)
1	15	497.5	50.5	49.5	0.9
	30	504.7	24.0	76.0	2.3
	45	516.2	11.4	88.6	4.6
	60	564.5	7.0	93.0	14.4
2	15	358.7	35.5	64.5	6.8
	30	394.0	15.5	84.5	17.3
	45	435.6	4.3	95.7	29.6
	60	474.1	3.3	96.7	41.1
3	15	265.6	48.0	52.0	2.7
	30	280.2	20.4	79.6	8.3
	45	300.9	7.8	92.2	16.3
	60	339.0	5.0	95.0	31.0
4	15	243.2	41.3	58.7	-3.8
	30	244.0	14.7	85.3	-3.4
	45	248.9	8.3	91.7	-1.5
	60	273.4	4.8	95.2	8.2
5	15	397.5	63.8	36.2	10.9
	30	398.7	35.0	65.0	11.3
	45	436.8	16.2	83.8	21.9
	60	528.7	7.5	92.5	47.6
6	15	181.4	40.4	59.6	5.3
	30	183.6	28.5	71.5	6.6
	45	211.9	12.0	88.0	23.0
	60	243.3	11.3	88.7	41.2

For each nozzle height and type, the maximum and minimum percentages of wetted areas were calculated over the ten samples (Table 4). For a specific nozzle type, the difference between maximum and minimum percentages of wetted area was shown in Table 4 to decrease with increasing nozzle height indicating better coverage uniformity. The mean of wetted area percentage values (Y), Coefficient of Variation (CV) and Uniformity of Distribution (UD) were calculated over the ten samples for each nozzle type at each nozzle height (Table 5). Information in Table 5 reveals that the Y and UD values were proportional to nozzle height, while the CV was inversely proportional to nozzle height, which is in agreement with the results shown in Table 2. This was attributed to the fact that as the nozzle height increased; the overlap from the side nozzles increased producing higher density of spray on the WSP samples and better spray distribution, resulting in lower CV values. These findings coincide with the results reached by Faqiri and Krishnan (2005). As shown in Table 5, nozzle No. 1 exhibited the highest average coverage density represented by values of Y of above 60% at all nozzle heights.

However, the lowest CV value of 8.5% and highest UD value of 91.5% were associated with nozzle No. 4 at 60 cm nozzle height.

Table 3: Samples taken from the water sensitivity papers under nozzle No. 1.

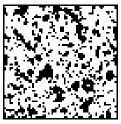
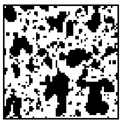
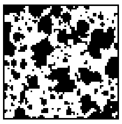
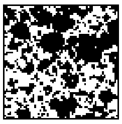
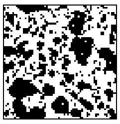
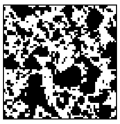
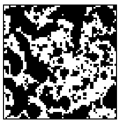
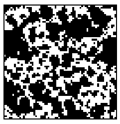
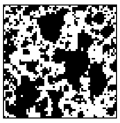
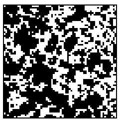
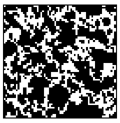
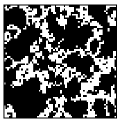
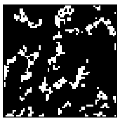
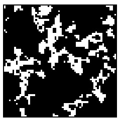
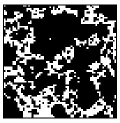
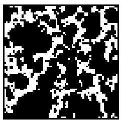
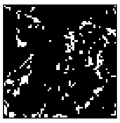
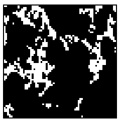
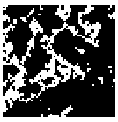
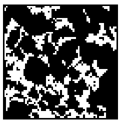
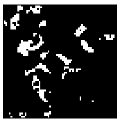
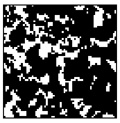
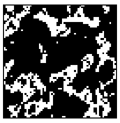
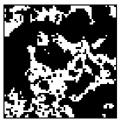
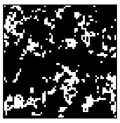
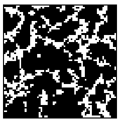
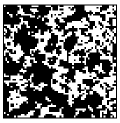
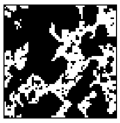
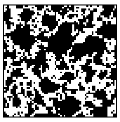
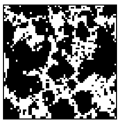
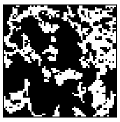
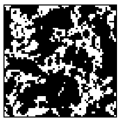
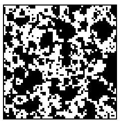
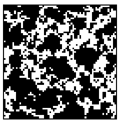
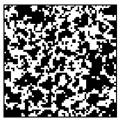
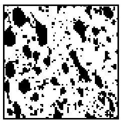
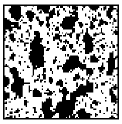
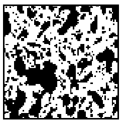
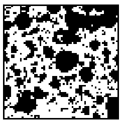
Sample no	height (15 cm)	height (30 cm)	height (45 cm)	height (60 cm)
1	 30.2	 40.9	 44.7	 53.6
2	 42.5	 53.4	 56.9	 60.3
3	 53.0	 58.6	 62.7	 67.1
4	 85.3	 78.5	 69.2	 68.4
5	 89.8	 81.4	 76.4	 70.5
6	 90.9	 73.8	 72.4	 68.6
7	 80.1	 73.0	 69.4	 67.2
8	 57.1	 62.3	 65.1	 66.7
9	 43.0	 54.7	 62.5	 65.9
10	 29.7	 38.8	 42.3	 45.6

Table 4: Maximum and minimum wetted area percentages of WSP samples.

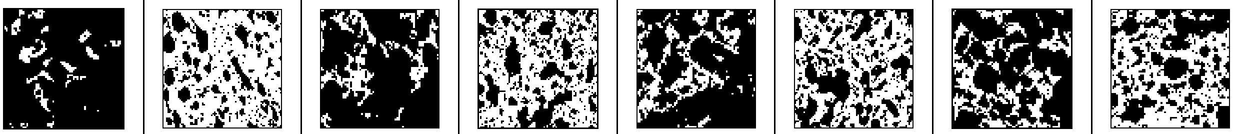
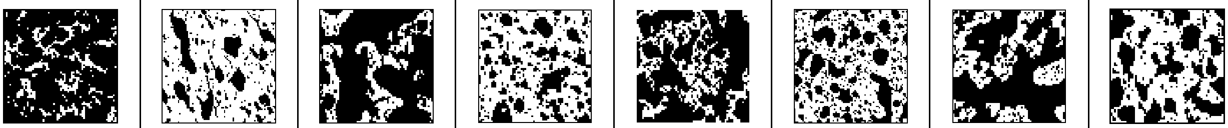
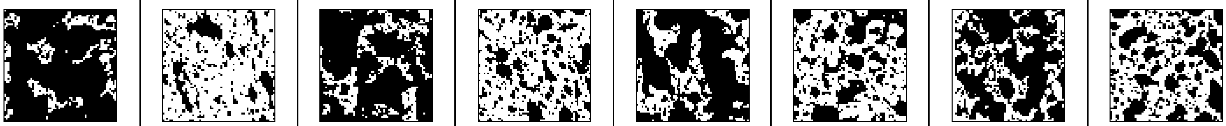
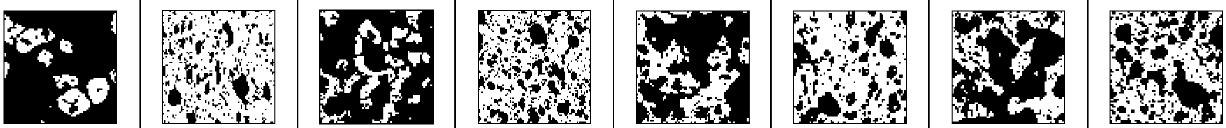
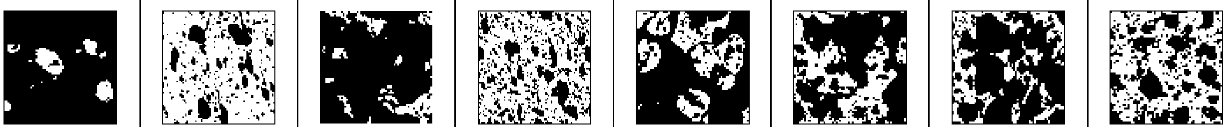
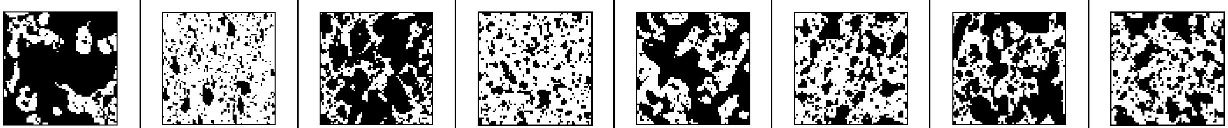
Nozzle No	Height (15 cm)		Height (30 cm)		Height (45 cm)		Height (60 cm)	
	max.(%)	min.(%)	max.(%)	min.(%)	max.(%)	min.(%)	max.(%)	min.(%)
1 	(90.9)	(29.7)	(81.4)	(38.8)	(76.4)	(42.3)	(70.5)	(45.6)
2 	(81.9)	(27.1)	(74.6)	(34.2)	(71.6)	(40.2)	(64.4)	(43.6)
3 	(83.3)	(25.1)	(76.7)	(33.3)	(69.7)	(41.4)	(62.3)	(43.4)
4 	(82.6)	(23.6)	(73.1)	(34.1)	(68.5)	(38.4)	(61.3)	(43.8)
5 	(91.5)	(22.7)	(87.3)	(32.1)	(75.6)	(39.7)	(70.8)	(42.6)
6 	(73.1)	(20.3)	(66.4)	(25.1)	(63.8)	(39.4)	(60.7)	(43.4)

Table 5: Statistical data of WSP samples.

Nozzle No.	Height (cm)	Y (%)	CV (%)	UD (%)
1	15	60.2	40.5	59.5
	30	61.5	24.4	75.6
	45	62.2	18.2	81.8
	60	63.4	12.6	87.4
2	15	53.9	40.7	59.3
	30	55.2	30.2	69.8
	45	57.3	21.3	78.7
	60	58.7	12.1	87.9
3	15	53.9	46.1	53.8
	30	55.4	28.6	71.4
	45	55.8	17.7	82.3
	60	57.0	9.9	90.1
4	15	53.0	43.4	56.6
	30	53.4	29.2	70.8
	45	54.7	19.0	81.0
	60	55.8	8.5	91.5
5	15	55.6	49.4	50.6
	30	57.3	36.8	63.2
	45	58.1	20.7	79.3
	60	59.1	15.5	84.5
6	15	46.3	43.8	56.2
	30	47.4	32.9	67.1
	45	50.3	18.1	81.9
	60	51.3	10.9	89.1

CONCLUSIONS

A ground field sprayer was utilized to study the effect of nozzle type and height on spray density and distribution on the targeted areas. Six different nozzle types were tested at four different nozzle heights. A conventional spray patternator was used to collect the spray liquid out of the nozzles and application rates and uniformity of distribution were calculated. The use of water sensitive papers (WSPs) in determining application density and distribution was also explored. The following conclusions are drawn from the study:

- For all nozzles tested, initial data revealed that the difference in the weight of water collected directly under the middle nozzle and that collected at nozzle sides decreased with increasing nozzle height. For nozzle No. 1, the difference reached 7.5 g at nozzle height of 15 cm, however, this difference decreased to only 0.7 g at 60 cm nozzle height indicating better spray distribution at greater nozzle heights.
- On the average, the application rate collected under the middle nozzle was found to increase with increasing nozzle height for all test nozzle types. For example, the

average application rate for nozzle No. 2 increased by more than 32% as the nozzle height increased from 15 to 60 cm. That was attributed to the fact that the overlap from the side nozzles increased with increasing nozzle height.

- For all nozzles tested, the application rate error and uniformity of distribution (UD) were shown to be proportional to nozzle height. For instance, the UD for nozzle No. 5 increased from 36.2% to 92.5% as the height increased from 15 to 60 cm, however, the error in application rate increased from 10.9% to 47.6%. Therefore, a compromise needs to be made to select the nozzle height that would provide adequate coverage uniformity with minimum application rate error.
- The flat fan nozzles were found to provide a better spray distribution at all nozzle heights compared to hollow cone nozzles. In addition, the application rate error produced by the flat fan nozzles, except for nozzle No. 2, was revealed to be less than the error produced by the hollow cone nozzles at all nozzle heights.
- For all nozzle heights and types, water sensitive paper (WSP) analysis revealed that the highest percentage of wetted area was associated with the middle samples located right under the nozzle. For a specific nozzle, the average wetted area percentage (Y) that was used to express density of spray coverage and the UD increased with increasing nozzle height. For example, Y increased for nozzle No. 2 from 53.9% to 58.7% and the UD increased from 59.3% to 87.9% as the nozzle height increased from 15 cm to 60 cm.
- WSP analysis was found to show the same general trend revealed by the conventional water collecting method, which makes it a reliable means to measure the characteristics of spray applications.

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