Backpack magnetic sprayer: off-target drift and on-target deposition uniformity in a sugarcane plantation

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Abstract: There is an increasing requirement for new application methods that are capable of minimizing agricultural spray drift and maximizing on-target deposition. Magnetic charge spraying techniques improve the adhesion characteristics of the spray solution to agricultural crops which in turn can reduce the amount of solution to be sprayed in comparison with the conventional spraying method that uses non-charged spray droplets. In this research, experimental field studies were conducted to evaluate the effects of magnetic spraying technology taking into account the effect of meteorological parameters on spray drift and on-target deposition in a sugarcane plantation. The results showed a significant benefit from magnetic spraying on drift reduction, in comparison with conventional knapsack and backpack boom sprayers. The lowest drift values were achieved with magnetic sprayer with TeeJetXR110015 nozzle; it was significantly lower than conventional backpack boom sprayer with both TeeJetXR110015 and TeeJetXR11001 nozzles and knapsack sprayer. Significant differences between treatments were also observed for on-target spray deposits at both top and middle canopies. The highest deposition was obtained by magnetic sprayer with TeeJetXR110015 nozzle at both upper and middle canopies. However, the deposition for the magnetic sprayer coupled with TeeJetXR11001 nozzle was statistically at par with knapsack at upper canopy and with both knapsack and backpack boom sprayers with TeeJetXR110015 nozzle in middle canopy. None of the application methods except magnetic sprayer with TeeJetXR110015 gave acceptable spray deposition uniformity. In conclusion, the result clearly showed that the potential of magnetic spraying technology in reducing pesticide drift and improving on-target deposition in crop spraying.

Keywords: magnetic sprayer, nozzle, drift, deposition, drift curve, sugarcane
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1 Introduction

Sugarcane is an important crop widely cultivated for multiple purposes by smallholder farmers in sub-Saharan Africa[1] and also by commercial farms. For instance in Ethiopia, sugarcane is an important commercial crop and it is the sole source of sugar produced by Ethiopian commercial mills and the industry plays a significant role in the country's economy[2]. Currently the total area under sugarcane plantations in the country is about 65 363 km^2 with an estimated production of approximately 400 000 t/a[3].

Among the many factors that constrain sugarcane yield, weeds are the major ones causing cane yield loss in the range of 41%-51%[4]. The control methods for weeds in sugarcane plantations include mechanical cultivation, manual cultivation, and application of herbicides. Mechanical and chemical means of weed control are the major methods in Ethiopian sugarcane plantations. Often non-availability of labor makes herbicidal weed control the major mechanism of weed management in the plantations[5]. Moreover, timely weed control is difficult as the fields are muddy making it inaccessible for hand weeding option. Knapsack sprayer using a single nozzle lance has dominantly been used for applying herbicides[6]. However, this method of application is compounded with many problems such as high drift[7,8] often associated with low on-target deposition resulting in high usage of both chemical and water. Owing to the fact that a single lance knapsack sprayer only covers 75 cm, the lance has to swing from side to side while walking to cover the spacing between furrows (91 cm) which usually results in large area of under-and-over application[6]. Moreover, spraying with knapsack results in higher variability in deposition because of the difficulty to maintain a constant spraying pressure and consistent walking speed[9]. The effectiveness of all chemical pesticide depends on the user’s ability to place the correct quantity of chemical on the intended target with the minimum loss to the environment[10].

According to previous research by Spray Drift Task Force[11], drift levels can be minimized by applying the coarsest droplet size spectrum that provides sufficient coverage and pest control, using the lowest nozzle height that provides uniform coverage and applying pesticides when wind speeds are low and consistent in direction. As an alternative to improve the deposition of spray on the target, electrostatic spraying has long been proposed as a prevention of chemical waste and environmental pollution by drift[12,13]. There have been significant advances in the research and development of electrostatic-spraying technology for agricultural and biological applications during the 20th century as summarized in the review by Law[13].

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An equivalent technology to electrostatic spraying is charging with a permanent magnet which has recently been introduced as an alternative option for the optimization of pesticides through mitigating drift and enhancing on-target deposition. The permanent magnet is a replacement for charging by electrostatic methods. The underlying justification for the physical process, as mentioned by the patent owner[14] is that the transiently magnetized particles are attracted to the living portions of the plants toward which they are aimed, including the leaves, stems, and trunks.

Magnetic force (MF) due to charging adds an additional force possibly in the direction where the biological surfaces of living crops are found. In the case of downward pesticide application (like backpack and boom sprayers), the magnetic force is added to the gravitational force that improves the deposition of the droplet on the target plant. Even in applications that are directed in other directions (horizontal, inclined or upward), this additional force can partially overcome the force due to gravity and kinetic energy imparted to the droplets. Additionally, this force can help the small droplets (<150 μm), which have high surface area to volume ratios that make them more vulnerable to air drag forces, to settle on the target surface. However, there is no literature on the scientific and engineering understanding of the magnetic action that proves this apart from the patent paper[14] and some explanatory application research by Wageningen University and Research[15]. In other fields, however, there is a significant volume of knowledge on beneficial effects of MF including effects on germination, plant development, photosynthesis and others[16], magnetic treatment of different irrigation water types on water productivity and yield[17] and other benefits also reported[18].

Recently, sprayer manufacturers introduced a magnetic spraying system which is based on fitting permanent magnetic inserts of a particular design and located in specific locations of sprayer with the intention to impart a magnetic charge into the liquid to cause the liquid to be easily attracted to the target plant. In this regard, the magnetic spray technology (MagGrow), patented by an Irish based company called MagGrow, has shown greater improvement and the company has claimed the technology reduces drift by over 80%, and delivers superior crop coverage by facilitating fine spray droplets[19]. A structured controlled test conducted by the University of Florida Cooperative Extension Service Institute of Food and Agricultural Sciences[14] confirmed magnetic spray is advantageous over conventional spraying apparatus owing to only 2% drift, 98% coverage, and 75% reduced chemical, resulting in better control of pests. Spray drift experiments in the Netherlands using this technology showed that a magnetically equipped sprayer in combination with the Hypro11003 flat fan nozzles and UB8503 end nozzles and 40 cm boom height over crop canopy resulted in a spray drift reduction of 33.1% when compared with a conventional boom sprayer in combination with an XR11004 flat fan nozzle at 50 cm boom height[15].

Therefore, the objective of this study was to evaluate spray drift and on-target spray deposition from a magnetically equipped sprayer using two nozzles that produce “fine” droplet spectra as defined by ASAE Standard S572[20] against conventional backpack boom and the widely used knapsack sprayers taking into account the effect of meteorological parameters. The hypothesis in selecting these two fine nozzles was that fine droplets could produce better target deposition with minimum ground drift using magnetic spraying.

2 Methods and materials

2.1 Study area and experimental field

The study area is within Oromia region, Ethiopia at the oldest sugarcane plantation called Wonji Sugar Factory (8°30'N to 8°35'N; 39°20'E; 1540 m.a.s.l.). A cropped sugarcane field was used to conduct the drift and deposition experiment. The area receives an average annual rainfall of 831 mm, with mean annual maximum and minimum temperatures of 27°C and 15°C, respectively.

2.2 Treatments and data sampling

Field deposit and drift experiments were carried out to measure the target deposit and drift values under field conditions for different spraying methods according to ISO Standard 22866[21]. The experiments involved five treatments: a magnetic sprayer (MagGrow) with two nozzles, a backpack boom sprayer with two nozzles and a knapsack sprayer that is currently widely used in the plantation. In order to avoid external sources of variability, all the working parameters were kept as constant as possible in all treatments. The sprayers were calibrated to apply water only at a constant rate for each replication and at the recommended operating pressures and application rates. Treatment combinations are summarized in Table 1.

Spray drift and deposition were collected using water sensitive paper (WSP) (76 mm×26 mm), which is specially coated yellow surface that changes color to blue when exposed to moisture. WSPs were used in many drift and deposition studies[22–25].

Table 1 Detail of treatment combination and application parameters

Application technique	Nozzles type	Treatment code	Pressure/bar	$D_{v0.5}$	Volume applied/L hm^{-2}
Knapsack sprayer	Full cone(FCX) 80	kn	2.0-3.0	214	250.0
MagGrow backpack	TeeJet: XR01 (F110)	Mg01	1.8-2.0	137	95.8
MagGrow backpack	TeeJet:XR015 (F110)	Mg015	1.6-1.8	165	96.7
Boom backpack sprayer	TeeJet: XR01 (F110)	Bm01	1.8-2.0	143	95.8
Boom backpack sprayer	TeeJet: XR015(F110)	Bm015	1.6-1.8	158	96.7

2.3 Experiment setup

To measure the amount of spray drift, wooden poles of 4 m high with WSPs were used and placed downward from the target sprayed area in the direction of the wind. The WSP was placed at 0.6 m height, equivalent to the crop height. The horizontal distance between each pole was 1, 5, 10 and 20 m from the edge of the sprayed plots (the last nozzle), this enabled to measure drift up to 20 m from the edge of the target sprayed zone. The layout for field drift measurements is shown in Figure 1. Two additional collection lines (B and C in Figure 1) with the same number of poles at the side of the first line were placed with randomized complete block design. Additional 12 WSP were placed at top and middle canopy (6 for each) to determine the deposits on the target plants. The middle canopy collectors were placed at 30-40 cm above the ground while the top collectors were placed at the tip of the plant. The measurement was replicated three times. A total of 24 WSPs (12 for horizontal drift and 12 for on-target deposition) were collected for each treatment per replication. The study was conducted on Sep. 15, 2016 and then the entire experiment was repeated on the following two days (Sep. 16 and Sep. 17). During the test, the sprayer went from right to left or vice versa at a constant average human walking speed (4 km/h).

After each spraying, the WSP were collected and placed in sealed bags which were later scanned by a scanner with a resolution of 600 dpi at an 8-bit gray-scale for image analysis. An image analysis method was used to measure spray deposit and drift on the WSP using DepositScan software[26]. The distribution of spray deposit, droplet density (deposit per area), coverage and amount of spray deposits per unit area was reported by the software. Spray deposits per unit area normalized by application volume was used for the analysis.

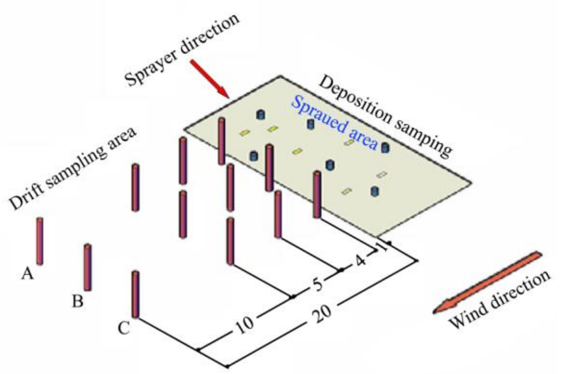


Figure 1 Field layout for field studies (m)

2.4 Meteorological Conditions

The experiments were conducted in 2016 outside the rainy season. At the start of each measurement, wind speed at 1 m height was recorded with a hand-held anemometer and air temperature and relative humidity were collected at nearby meteorological station within 200 m from the experimental site. The applications were made in the mornings, in most cases at air temperature below 20℃ and relative humidity above 50%, and always at comparable wind velocity between treatment applications. All tests were conducted with a mean wind speed above 1.0 m/s (ranges from 3.6 to 4.8 m/s) and the direction did not deviate more than 30° relative to the crop rows and spray track as indicated in the standard protocol.

2.5 Spraying technique and descriptions

Magnetic sprayers are not electrostatic sprayers. They induce a magnetic charge on spray droplets instead of an electrostatic or ionic charge on the droplets. Magnetic sprayers use hollow neodymium DC magnets throughout the spray system. These magnets are strong enough to induce a magnetic charge in the liquid spray solution. The MagGrow products are based upon the premise of fitting magnetic inserts in specific locations on a sprayer which imparts a magnetic charge into the sprayed liquid. The equipment used was a backpack with 15 L tank and 6 nozzles boom. The nozzles are installed vertically on the boom at equal interval of 50 cm on 3 m long boom. The magnets are positioned at two positions: below the tank within a manifold through which the spray liquid flows towards the spray boom and at each nozzle body. It is operated with Black and Decker lithium battery. The second sprayer was the boom sprayer which is similar to the MagGrow sprayer but without the magnetic charging system.

The Knapsack treatment was hand actuated using high-discharge hollow cone nozzle at a height above the canopy between 0.4 and 0.6 m. The nozzle used in the study was selected from among the most commonly used in sugar plantations. Application walking speed and working height was set at 4 km/h and 0.5 m above crop canopy for MagGrow and conventional boom sprayers respectively. For knapsack application method, the walking speed and height were set at 2-3 km/h and 0.5 m respectively. All working parameters for knapsack sprayer were established following the local famers' practices. The research operators practiced to achieve the stated application parameters prior to the application.

2.6 Analysis

For comparison of treatments, the spray drift and deposition were normalized by expressing the spray drift as percentage of the applied spray volume[21]. The percentage reduction in drift by charged sprayer is calculated as the reduction in drift on a horizontal surface when compared with non-charged sprayers.

The analysis was made using R statistical software (version 4.0.2)[27] using the following packages: lem4[28], relaimpo[29], agricolae[30], ggplot2[31] and R base packages. Prior to the analysis, the dataset was examined for normality and homogeneity of the variances assumptions using Shapiro-Wilk and Levene tests respectively. If the assumptions were not met at 5% probability, the data were transformed using either the arcsine or square root transformation and subjected to a new analysis. The following four analyses were made separately:

(1) Drift percentage was analyzed in linear mixed-effects model as repeated measure in distance to test whether a) treatment affects percentage drift, b) there is an effect of distance on drift, c) there is an interaction (i.e. drift response to treatment depends on distance).

(2) Drift percentage was analyzed using linear mixed-effects model to see effect of meteorological parameters on drift. Application methods and collection point as fixed effect and meteorological parameters as a covariant.

(3) Target deposition was analyzed with a separate linear model with application method as fixed effect.

When a significant difference was found, means separations were made for both percentage drift and deposition using Tukey's test, at 5% probability. The drift results of the same application method at different drift collector points were compared. Residual analyses were also performed to check if the assumptions were met in all cases.

(4) Lastly, curve fitting was performed between drift percentage and distance for each application method separately for different wind speed groups. The regression parameters of each application method were analyzed using analysis of variance (ANOVA) to check whether the difference is significant or not.

The relationship between percentage drift and distance is represented by nonlinear relationship using power-law function as Equation (1)[32].

$$DP = aD^b \tag{1}$$

where, DP is drift percentage (%) expressed as the percentage of the applied dose at a distance (D) expressed in meter (m); a and b are regression parameters.

3 Results

3.1 Ground drift

Drift percentage was assessed in a mixed-effects model in repeated measure in distance. Fixed effects were application method, collection point and application day, and wind speed was a covariant to account for the difference in wind speed in replications and application day. The ANOVA test in the main effect indicated that there is a highly statistically significant effect of application methods and collection points on horizontal percentage drift ($p<0.001$). Application day was also significant so the data were not pooled. The significant difference in drift percentages at different distances ($p<0.001$) indicated non uniform distribution along the downward distance. In the interaction term, there was statistically significant interaction between application method and collection point ($p<0.001$) and also between collection point ($p<0.001$) with wind speed.

A visualized effect (Figure 2) of distance on horizontal drift by application method fitted with a linear mixed-effects model clearly showed that application method Bm01, Bm015 and Kn have a steeper slope with downwind distance (that is, they have a faster decrease), compared to charged treatments (Mg01 and Mg015). Also Figure 2 shows that there was significant interaction between treatments and considerable effect size (i.e. the lines are not parallel to each other).

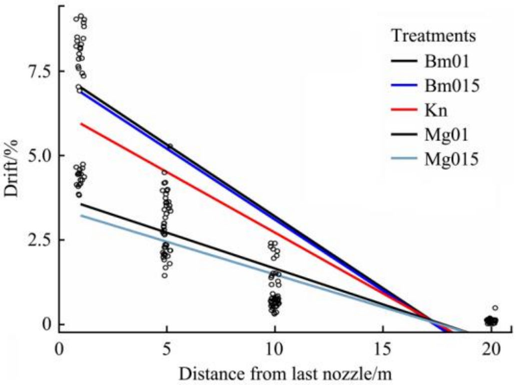
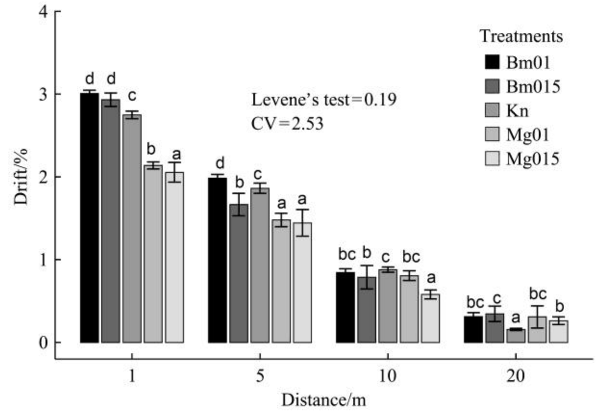
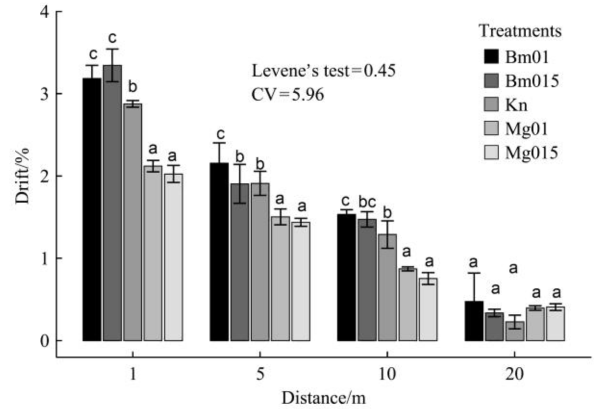


Figure 2 Interaction between horizontal drift percentage and distance by application method

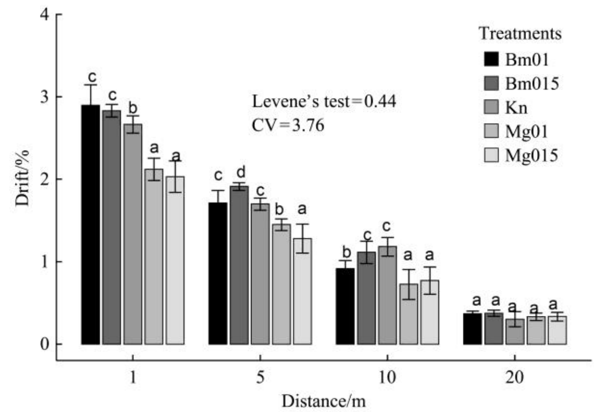
To separate the means, single factor ANOVA was conducted separately for each collocation point and application day to avoid an unambiguous interpretation of the main effects due to interactions. Comparison between application method for each downwind distance and application day is presented in Figure 3. The application methods significantly affected percentage drift in all sampling points in each application day except at 20 m collection point on the second and third application day. On average across the application days, the boom sprayer with the XR01 nozzle (Bm01) resulted in the highest percentage drift at all sampling point except at 5 m and 10 m sampling points at the third application day, followed by boom sprayer with XR015 nozzle (Bm015) and knapsack sprayer, whereas magnetic charging (both with XR01 and XR015 nozzles) resulted in the lowest drift percentage. When comparing between magnetic charging treatment Mg01 and Mg015, the Mg015 gave the lowest percentage drift but statistically, there was no difference between the two in most cases. In the aggregate mean up to 15 m from the edge of the treated area, it was observed that the Mg01 and Mg015 treatments significantly lowered the drift percentage by a percentage of 41.4% and 49.5% respectively as compared to Kn treatment. In comparison between boom sprayers with the same nozzle but with and without charging, Mg01 lowered drift percentage by 48.07% as compared with BM01 and Mg015 by 53.47% as compared with Bm015. The difference between treatments was reduced at 20 m distance in all the application days. Treatment Kn, Bm01 and Bm015 resulted in 3.3%, 3.84% and 3.35% drift percentage at 5 m away from the treated area respectively while for treatment Mg01 and Mg015, the percentage drift was 2.18% and 1.93% respectively at 5 m. Beyond 10 m, the percentage drift was below 1.5% for all application methods.



a. Application day 1



b. Application day 2



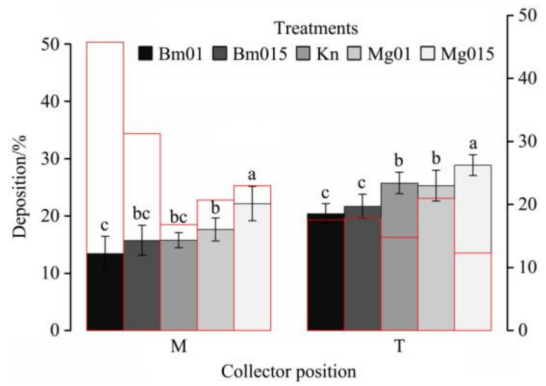
c. Application day 3

Note: Different letters within each distance indicate statistical significance at a = 0.05 with Kenward-Roger degrees of freedom method and Tukey method p-value adjustment. The error bar is SD. The data is transformed by square root transformation.

Figure 3 Mean percentage drift by application methods and for each application day

3.2 Spray deposition

The tests for normality and homoscedasticity indicated that data transformation was not necessary. The ANOVA test in the main effect (deposition) indicated that there was a significant difference in deposition between the application methods ($p<0.001$) and also between the positions sampled ($p<0.001$) but there was no significant effect of wind speed ($p=0.65$) on deposition. In the interaction term, there was a statistically significant interaction between application methods and wind speed ($p<0.001$). The average spray deposit at the top and middle canopy varied from 20.4% to 28.8% and from 13.42% to 22.1% among the 5 treatments, respectively (Figure 4). The deposition values found with Mg015 application method were the highest while Bm01 values were the lowest at both top and middle canopy. The mean deposition of Mg015 was statistically different from the uncharged application methods (Kn, Bm01 and Bm015) at the middle canopy and also different at top canopy compared to Bm01 and Bm015. Mg015 showed no significant difference with Kn at the top canopy. Mg01 application method tended to produce higher deposition on the middle canopy as compared to the uncharged boom sprayers (Bm01 and Bm015) and knapsack but not significantly different from knapsack. In general, it was observed that the Mg015 treatments significantly increased deposition by a percentage of 41.5%, 33.13% and 12.1% as compared to Bm01, Bm015 and Kn treatments respectively at the top canopy while in the middle canopy, it increased by 40.7%, 65.0% and 40.6% compared with the Bm01, Bm015 and Kn treatments, respectively. Mg01 increased deposition by a percentage of 23.9% and 16.6% as compared to Bm01 and Bm015 treatments respectively at the top canopy but no improvement as compared to Kn. In the middle canopy, Mg01 improved 31.4%, 12.15% and 12.0% as compared to Bm01, Bm015 and Kn treatments, respectively.



Note: Bars with a different label are significantly different. The red bar is the C.V.

Figure 4 The means (mean SE) and coefficients of variation (C.V.) of the relative depositions at top (T) and middle (M) canopy

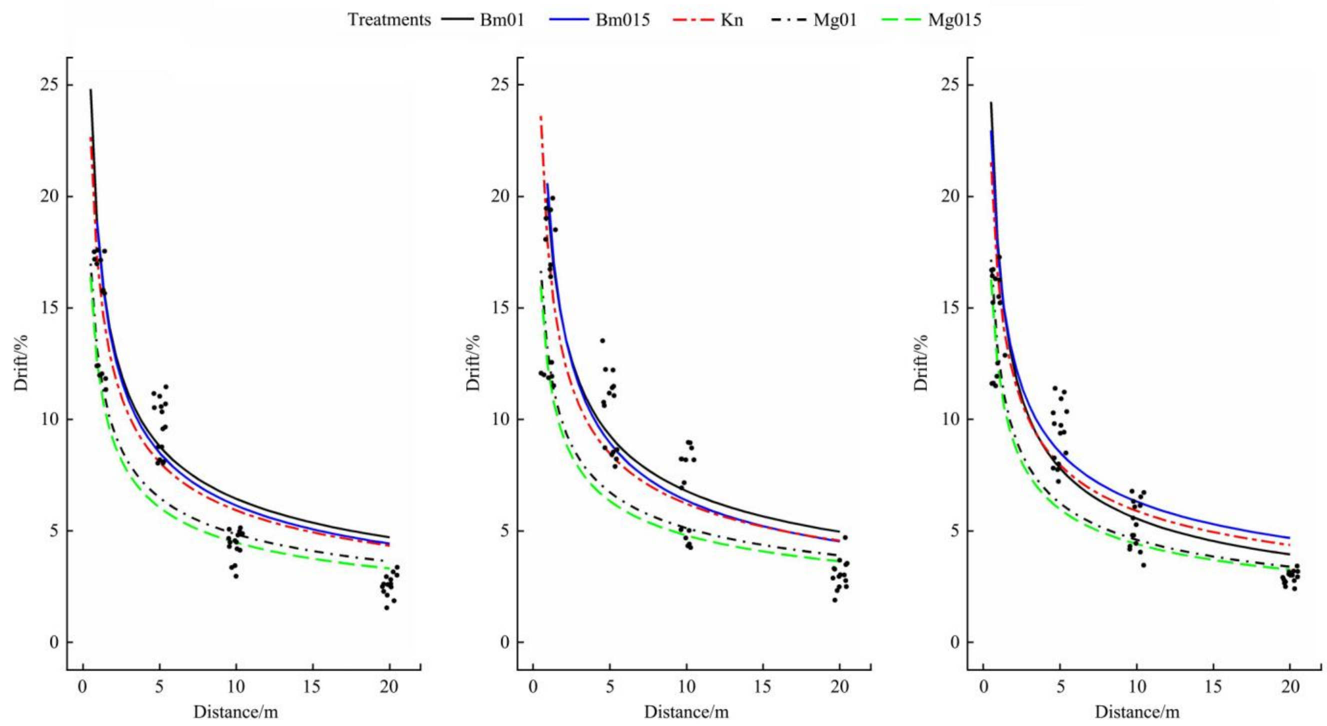
In terms of the uniformity of the distribution of the spray disposition in the canopy, the coefficient of variations (CVs) which was computed by dividing the standard deviation by the mean of the spray deposit, showed no significant difference between application methods at the top canopy but significant difference at the middle canopy. Mg015 gave the least CV at the top canopy while Kn at middle canopy (Figure 4 with red bar).

3.3 Drift Curves

Drift curves were determined for all application methods on sugar cane crops under Ethiopian weather conditions. The spray drift data were aggregated per wind speed in to three groups and linearized using arcsine transformation and subjected to nonlinear regression analysis to identify the best fits separately for each group. Exponential decay and power function models were tested. The regressions of both models provided adequate account of the variance in the dataset and satisfactory residual sums. The difference between the two models was found to be insignificant and thus power model was used. Previous studies[33-36] also used exponential and power models.

The estimated parameters (Equation (1)) representing the drift curves together with fitted equation r^2 values for each application method and wind speed group are shown in Table 2. The drift data were well described by the fitted power curves as indicated by the relatively high r^2 values ranging from 0.85 to 0.94 and low standard errors of the parameter estimates. On average, the power model accounted for 88.6% of the variability in the data. The fitted drift curve for each application method is presented separately for each wind speed group (Figure 5).

Spray drift curves for all application methods showed that maximum drift percentages were obtained at the collection point closest to the sprayed area and decreased with increasing distance for all wind speed groups. In comparison between treatments, Bm01 gave the highest drift in the third wind speed group while Bm015 in first and second wind speed groups. Mg015 gave the least in all wind speed group followed by Mg01.



a. Wind speed at 3.6-4.0 m/s b. Wind speed at 4.0-4.4 m/s c. Wind speed at 4.4-4.8 m/s

Figure 5 Drift curves for different application methods for each wind speed group (Data were transformed by arcsine transformation)

Table 2 Regression parameters for each application method by wind speed group (Data was transformed by arcsine transformation)

Treatments	Wind speed at 3.6-4.0 m s^{-1}			Wind speed at 4.0-4.4 m s^{-1}			Wind speed at 4.4-4.8 m s^{-1}		
	a	b	r^2	a	b	r^2	a	b	r^2
Kn	16.0±1.18	–0.45±0.06	0.87	16.7±1.10	–0.44±0.06	0.86	17.4±1.77	–0.45±0.09	0.86
Mg01	12.6±0.63	–0.42±0.04	0.88	12.8±0.82	–0.41±0.05	0.89	12.9±1.97	–0.45±0.13	0.89
Mg015	12.1±0.61	–0.44±0.04	0.89	12.2±0.81	–0.43±0.06	0.89	12.4±1.72	–0.40±0.11	0.89
Bm01	16.9±1.08	–0.48±0.06	0.94	18.2±1.11	–0.47±0.06	0.88	19.0±1.41	–0.42±0.06	0.86
Bm015	17.1±0.89	–0.48±0.05	0.91	17.2±2.52	–0.42±0.12	0.89	19.4±1.04	–0.47±0.05	0.90

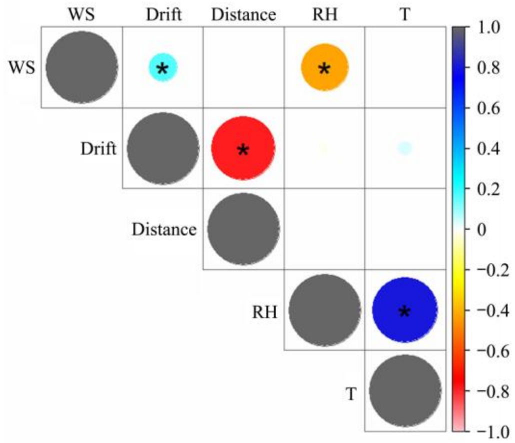
A separate analysis was done to determine whether the parameters of each application method differed and the result showed that both regression parameters (a) and (b) were significantly different. Means comparison for both of these regression parameters showed that spray quality (Table 1) had a significant impact on the downwind spray drift deposits arising from the application methods. Contrasts between the conventional sprayers and charged methods indicated highly significant differences in both regression parameters. The regression curves for the kn, Bm01 and Bm015 were found to be statistically coincident in the first and third wind speed groups. Comparison between curves for application with charging (Mg01 and Mg015) and the other three treatments were found to be statistically non-coincident in all wind speed group. The coincidence was intuitively apparent from examination of the results in Figure 4. In general, drift values were increased with wind speed at all collection points except for Mg01 treatment beyond 5 m. The summary of the drift change from wind speed group 1 (3.6-4.0 m/s) to wind speed group 3 (4.4-4.8 m/s) in percentage is listed in Table 3.

Table 3 Percentage change in drift values with wind speed change from 3.6-4.0 m/s to 4.4-4.8 m/s for each application method

Collection point/m	Change in drift values by treatments/%				
	Kn	Mg01	Mg015	Bm01	Bm015
1	14.0	3.1	4.0	19.2	22.2
5	15.0	–2.3	12.3	36.0	22.0
10	15.4	–4.7	15.7	42.1	21.9
20	15.7	–7.2	19.0	47.6	21.8

3.4 Effect of metrological parameters

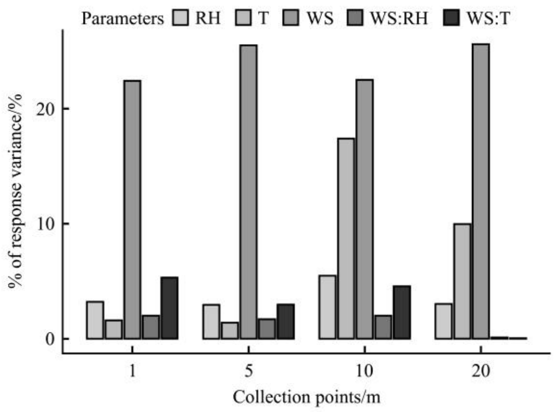
The effect of metrological parameters was assessed in a linear mixed-effects model separately for ground drift and on-target deposition. For ground drift the analysis was done by including application methods and collection point as fixed effect with separate intercept and slope for each of the five application methods. The analysis showed that the effect of wind speed (p= 0.11) on percentage drift was not significant in this study. The effect of other meteorological parameters (temperature and relative humidity) on drift had very little effect and only accounted for a very minor proportion of the variability in the measured drift. The low effect of temperature and relative humidity on ground drift can be explained by the small variation in the measured values. The correlation matrix (Figure 6) generated from Pearson's correlation matrix revealed that drift was strongly and negatively correlated with the downward distance. There was strong positive correlation between wind speed and ground drift. There was no strong relation between drift either with temperature or relative humidity.



Note: The sizes of the circles are proportional to the correlation coefficients and circle with "*" symbol represents the correlation is significant with p<0.05. (WS-wind speed, T- temperature and RT- relative humidity)

Figure 6 Correlation matrix between measured factors and drift

To better understand their relative importance in explaining ground drift, the relative importance of each and their interactions is calculated (R^2 partitioned by averaging over orders) separately for each collection point using 'relaimpo package'[29] and presented in Figure 7. Wind speed has the highest relative importance in all collection points followed by the interaction between wind speed and temperature. Their relative importance in explaining ground drift varied downward from the edge of the sprayed area. The relative importance of temperature increased from below 2% near the edge of the sprayed area (1 m and 5 m) to 18% at 10 m while relative humidity remained constant at all collection points.

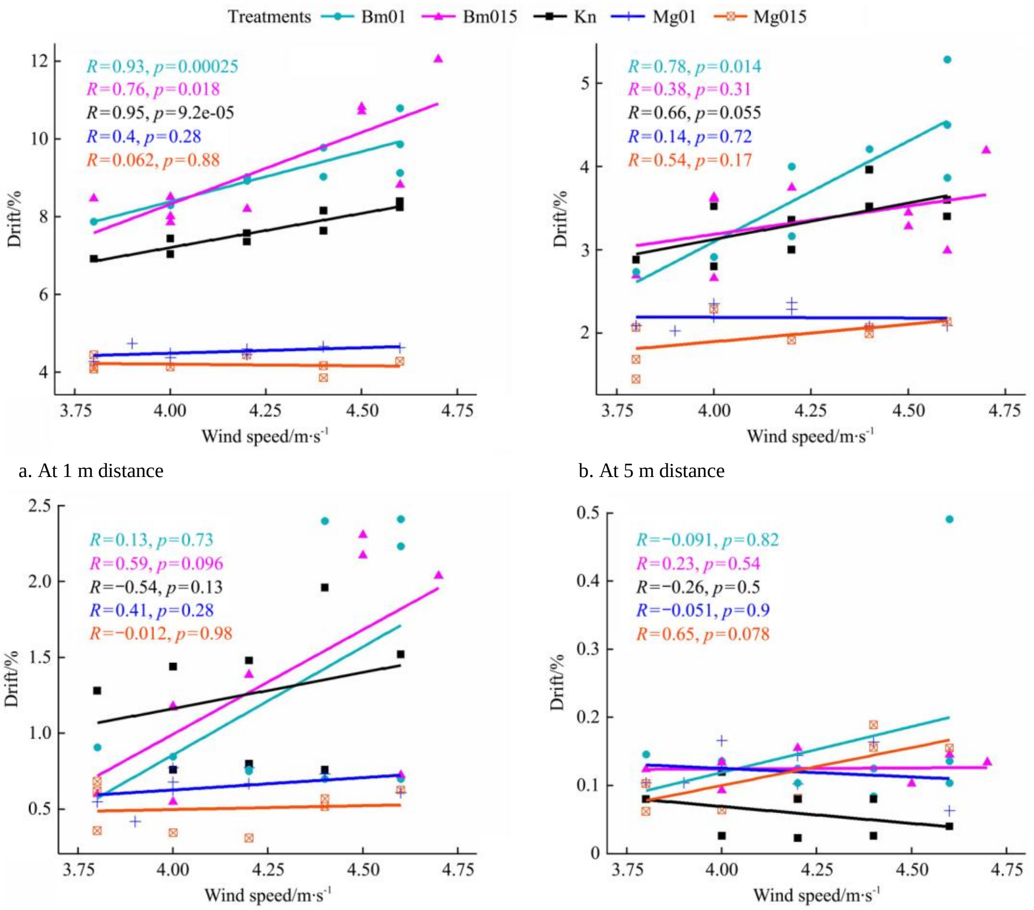


Note: WS – wind speed, T – temperature, RT – relative humidity, WS: RH – interaction between wind speed and RH and WS: T – interaction between wind speed and temperature

Figure 7 Relative importance of metrological parameters in explaining percentage of response variance

Figure 8 shows that there is a nearly linear relationship between mean percentage drift and wind speed for each application method at each collection point with unequal slopes and intercepts across application methods. Generally, treatment Bm01, Bm015 and Kn have the steepest relationship, with a lower intercept, while those of charged treatments appeared to be very similar in all collection points with lower slope as compared to the uncharged backpack boom and knapsack sprayers. It was shown that the effect of wind speed for uncharged treatments depends largely on downward distance with positive relationship up to 15 m. At 20 m, the relationship was weak and even became negative for Bm01 and Kn treatments. This was due to the fact that spray droplets might be carried away by stronger wind and didn't settle on the collector. For charged treatments, the drift values were much more stable under the effect of increasing wind speed and relatively remained the same for all collection points.

Correlations between wind speed and drift at each collection point were performed for each application method (Spearman rank tests with mean drift for each collection point) and presented together with significance level in Table 4. For near distance (1 and 5 m), significant correlations were observed between spray drift and wind speed for all uncharged treatments except for Bm015 at 5 m. No significant correlation was found for charged treatments (Mg01 and Mg015) at both distances (1 and 5 m). At a distance of 10 and 20 m, correlations were not significant for all application methods.



a. At 1 m distance

b. At 5 m distance

c. At 10 m distance

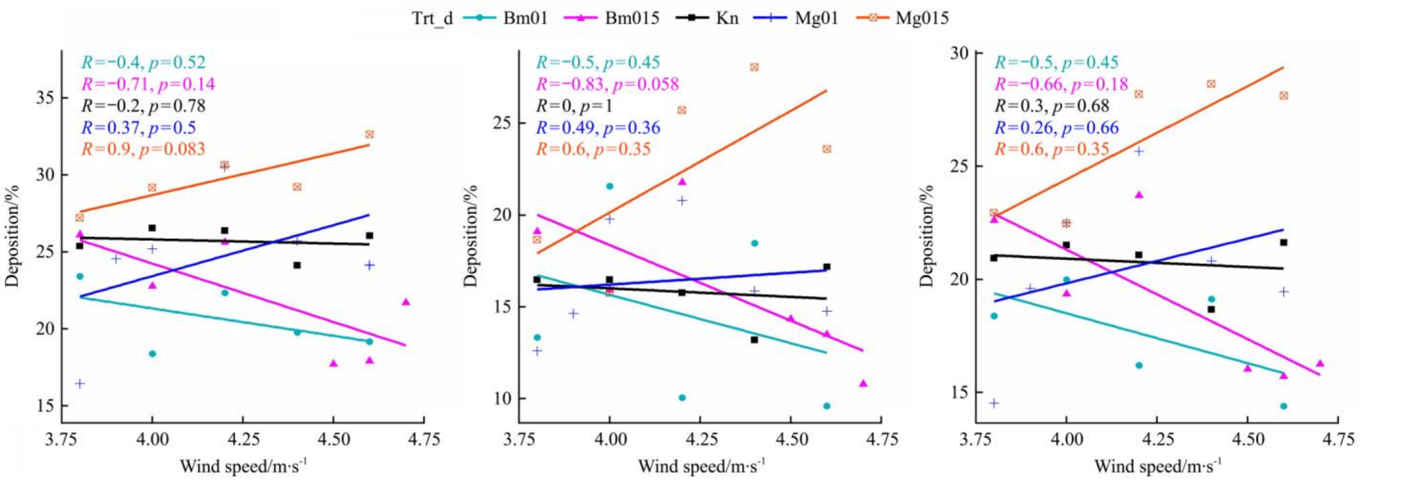
d. At 20 m distance

Figure 8 Effect of wind speed on drift at different collection points for each application method

Table 4 Correlations between wind speed and drift at each collection point by application method (Spearman rank tests with mean drift for each collection point)

Collection point/m	Kn		Mg01		Mg015		Bm01		Bm015	
	R	*P*	R	*P*	R	*P*	R	*P*	R	*P*
1	0.95	<0.001	0.4	0.28	0.35	0.35	0.93	<0.001	0.76	0.02
5	0.68	0.041	0.14	0.72	0.64	0.08	0.78	0.014	0.38	0.31
10	0.5	0.17	0.41	0.28	0.11	0.78	0.13	0.73	0.59	0.09
20	–0.26	0.49	–0.05	0.9	0.5	0.17	–0.11	0.77	0.23	0.55

With regard to the effect of wind speed on target deposition, with an increase in wind speed, the increment in both total deposit (Figure 9c) and deposit on the top (Figure 9a) and middle canopy (Figure 9b) is apparent for Mg015 and Mg01 treatments with more rate of change for Mg015. With knapsack treatment, the quantity deposited was independent of wind speed while for Bm01 and Bm015, the quantity deposited decreased with increasing wind speed. Correlations between wind speed and deposition at top, middle canopy and total deposition were performed for each application method (Spearman rank tests with mean deposition for each sampling position) and are presented with significance level in Table 5. The correlation between deposition and wind speed was positive for charged sprayers while for non-charged boom sprayers is negative. For knapsack, the correlation coefficient was almost zero. Correlations were only significant for Mg015 and Bm015 at top and middle canopy respectively.



a. At top canopy b. At middle canopy c. Total deposition

Figure 9 Effect of wind speed on deposition for each application method

Table 5 Correlations between wind speed and deposition at each collection point by application methods (Spearman rank tests with mean deposition for each collection position)

Collector position	Kn		Mg01		Mg015		Bm01		Bm015	
	R	P	R	P	R	P	R	P	R	P
Top	–0.2	0.75	0.37	0.47	0.9	0.037	–0.4	0.5	–0.71	0.11
Middle	0.0	1.0	0.49	0.33	0.6	0.28	–0.5	0.39	–0.83	0.042
Total deposition	0.3	0.62	0.26	0.28	0.6	0.28	–0.5	0.39	–0.66	0.16

The conditions placed on the analysis of three way ANOVA for both drift (after data transformation) and deposition data analysis were satisfied. The examination of normal probability plot indicated that a few observations were somewhat deviant from the fitted line. However, the test of normality indicated there is strong support for the normality of the residuals. The plot of the residuals versus predicted values did not indicate any violation of the equal variances of the residuals assumption because the spread in the residuals remained reasonably constant across the predicted values (Figure 10).

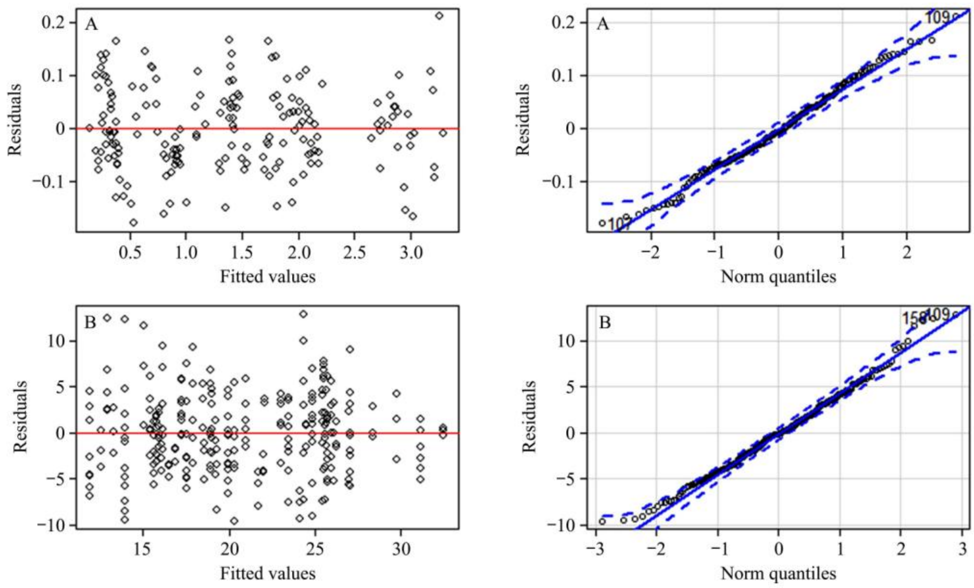


Figure 10 Residual analysis for ground drift “A” and deposition “B”

4 Discussions

Drift evaluation: the advantage of using magnetic sprayer has been effectively demonstrated as spray off-target drift was significantly decreased compared with a conventional backpack boom and knapsack sprayers. In the aggregate mean up to 15 m from the edge of the treated area, magnetic sprayer with TeeJet:XR11001 (Mg01) and TeeJet:XR110015 (Mg015) nozzles significantly lowered the drift percentage by a percentage of 41.4% and 49.5% as compared to Kn treatment respectively. Comparison with boom sprayer, Mg01 lowered drift percentage by 51.6% as compared with BM01 and Mg015 by 55.5% as compared with BM015. Only very limited peer reviewed published information is available to extensively compare the results with other works. However, spray drift experiment in the Netherlands using a similar technology but fitted in tractor boom sprayer reported that magnetic sprayer in combination with the Hypro11003 flat fan nozzles and UB8503 end nozzles and 40 cm boom height over crop canopy resulted in a spray drift reduction of 33.1% when compared with conventional boom sprayer in combination with an XR11004 flat fan nozzle at 50 cm boom height[15].

It was observed that meteorological variables alone explained very minor differences (<3%) when the analysis was done for combined dataset (all application methods and collection points combined). However, the variance explained by wind speed, when application methods and collection points were analyzed separately, ranged from 3.3% to 73.3%. The low prediction power of wind speed could be explained by the complexity of drift as measured under field conditions, also observed by García-Santos, Feola, Nuyttens, and Diaz[7]. Moreover, the additional factor (i.e. magnetic attraction) that affects the motion of charged particles might have contributed to altering the effect of wind speed. No published literature was found that reported charged particle motion under magnetic charging under different environmental conditions. Consistent with previous results from literature[37-39], there is a nearly linear positive relationship between mean percentage drift and wind speed for each application method but with unequal slopes and intercepts across application methods. In general, drift values were increased with wind speed at all collection point except for Mg01 treatment beyond 5 m. Similar results have also been presented in other studies. Bayat et al.[40], reported that increasing wind velocity increased downwind drift with less at a wind velocity of 1.5 m/s, compared with 2.5 and 3.5 m/s. Arvidsson et al.[41] also reported that the amount of initial off-swath droplet drift increased by about 0.94 percentage units for each unit of increasing wind speed (1 m/s). As compared to uncharged treatments, downwind drift was much more stable under the effect of increasing wind speed for charged sprayers. Lenhardt[14] also reported a wind of 5.36 m/s did not substantially affect spray drift using magnetic spraying. This suggested that with increasing wind speed, a more uniform deposit is likely to be achieved with charging using fine nozzle, as well as greater deposits on the middle part of the canopy. Therefore, with magnetic charging, it is possible to spray at a higher relative wind speed as compared to conventional sprayers.

The effect of temperature and relative humidity on drift was very little and only accounted very minor in the variability in the measured drift. The little effect of temperature and relative humidity on ground drift can be explained by the small variation in the measured values. Other studies also reported little influence of temperature and relative humidity on the variation of drift deposits[42].

Curve fitting was performed between drift percentage and downward distance for each application method separately for each application day using power law and exponential functions. The difference between the two models was found to be insignificant and thus power model was used owing to the fact that it is easy to compare curves and availability of other similar models such as Ganzelmeier et al.[43], The drift data were well described by the fitted power curves as indicated by the relatively high r^2 values ranging from 0.85 to 0.94 and low standard errors of the parameter estimates. In general, the drift curves for all application methods showed that maximum drift percentages, approximately 85% of the applied volume, were obtained at the collection point closest to the sprayed area and decreased with increasing distance. This pattern was also observed by other researchers[7,8], who obtained largest drift values at a distance of 1 m from the crop, using a knapsack sprayer.

Deposition evaluation: Magnetic sprayer with TeeJetXR110015 nozzle (Mg015) significantly increased deposition in both upper and middle canopy. The deposition value for magnetic sprayer with TeejetXR11001 nozzle (Mg01) was statistically at par with Kn at upper canopy and with both kn and backpack boom sprayer in middle canopy. Lenhardt[14] also reported that 98% of the magnetized spray reaches and adheres to foliage surfaces, on both top and bottom surfaces. The rationale for better performance of magnetic sprayer was explained by Lenhardt[14] as the transiently magnetized particles are attracted to the living portions of the plants toward which they are aimed, including the leaves, stems, and trunks. With regard to deposition uniformity, none of the application methods except Mg015 gave acceptable spray deposition uniformity. Previous research reported that spray uniformity with CVs less than 10% were very uniform, while those with CVs between 10 and 15% were acceptable and those with CVs greater than 15% were unacceptable[44]. With increasing wind speed, deposition increased for magnetic sprayer with both nozzles (TeeJetXR11001 and TeeJetXR110015), while deposits decreased with conventional boom sprayer with both TeejetXR11001 and TeeJetXR110015 nozzles. This suggested that, with increasing wind speed, a more uniform deposit is likely to be achieved with magnetic sprayer using fine nozzle, as well as greater deposits on the middle part of the canopy. For knapsack, wind speed did not affect the deposition. In general, deposition quantity was better at upper than at middle canopy for all application methods.

5 Conclusions

A magnetically charged sprayer system to reduce pesticide waste caused by ground drift and to enhance on-target deposition was assessed. The results obtained clearly showed that the magnetic sprayer decreased ground drift and increased on-target deposition with better uniformity as compared to conventional backpack boom and knapsack sprayers. From the results obtained, it can be concluded that:

Ground drift can best be reduced by using the magnetic sprayer with both TeeJet XR11001 and TeeJet XR11001 nozzles which significantly lowered the ground drift by more than 41.0% and 49.0%, respectively as compared to conventional backpack boom (Bm01 and Bm015 treatments) and knapsack sprayers.

Magnetic sprayer coupled with TeeJet XR110015 and TeeJet XR11001 nozzles provided improved on-target spray deposition at both top and middle canopy, while the conventional backpack boom sprayer with TeeJet XR11001 gave the lowest on target application. The highest performing treatment, magnetic sprayer with TeeJet XR110015 increased the deposition by 41.5%, 33.1% and 12.1% at the top canopy and by 40.7%, 65.0% and 40.6% at the middle canopy as compared to conventional backpack (Bm01 and Bm015 treatments) and knapsack sprayers, respectively. Deposition uniformity was also best with magnetic sprayer coupled with TeeJet TeeJet XR110015.

The magnetically charged sprayer, given its ability to reduce drift and enhance on-target deposition, can make an important contribution in reduction of spray chemical expenditure.

The effect of wind speed is more pronounced than the effect of relative humidity and temperature on ground drift and on-target deposition. However, the effect of wind speed on drift is reduced for magnetic sprayers as compared to non-charged sprayers. This has practical importance as it enables to spray at windy conditions where conventional sprayers could not be effective.

While this study could be considered successful in achieving the research goals, further research is needed to provide more findings under a wider variety of atmospheric conditions, different crop and application parameters in a controlled environment, to ensure greater advantage of the system. Additionally, it might be of interest to perform experiments to verify the expected gains in biological efficacy by magnetic spraying or by using a reduction in water application rates.

[References]

[1] Esayas T, Mekbib F, Shimelis H, Mwadzingeni L. Sugarcane production under smallholder farming systems: farmers preferred traits , constraints and genetic resources. Cogent Food Agric, 2016; 2: 1–15.

[2] Firehun Y, Tamado T, Abera T, Yohannes Z. Competitive ability of sugarcane (*Saccharum officinarum* L.) cultivars to weed interference in sugarcane plantations of Ethiopia. Crop Prot, 2012; 32: 138–143.

[3] Ethiopian Sugar Corporation (ESC). Sugar corporation and Ethiopian sugar industry profile. ESC; 2017. Available: http://www.etsugar.gov.et/index.php/en/ Acceesed on [2017-06-29]

[4] Taye E. Survey of weed flora and evaluation of some foliage applied herbicides in the sugarcane plantation of Wonji-Shoa and Metahara. Msc dissertation. Alemaya: Alemaya University of Agriculture, 1991.

[5] Firehun Y. Evaluation of aterbutex 50 SC against weeds at Tendaho Sugar project: pre-verification trial. In: Firehun Y, Dametie A, Negi T, Hundito K, Esayas T, Fantaye A, editors. Proc Ethiop Sugar Ind Bienn Conf. Addis Ababa, Ethiopia, 2009; pp.171–176.

[6] Ayalkebet T, Firehun Y, Zewdu A. Increasing the efficiency of knapsack sprayers by modifying a single nozzle sprayer into a low cost multi–nozzle sprayer. Eth J Weed Mgt, 2012; 5: 28–42.

[7] García-Santos G, Feola G, Nuyttens D, Diaz J. Drift from the use of hand-held knapsack pesticide sprayers in Boyacá (Colombian Andes). J Agric Food Chem, 2016; 64(20): 3990–3998.

[8] Franke A, Kempenaar C, Holterman H J, van der Zande J C. Spray drift from Knapsack sprayers: a study conducted within the framework of the Sino-Dutch Pesticide Environmental Risk Assessment Project PERAP. Wageningen, The Netherlands, 2010; Report No. 658.

[9] Miller A, Bellinder R. Herbicide application using a knapsack sprayer. In: Rice-Wheat Consortium for the Indo-Gangetic plains, New Delhi-110 012. New Delhi, India; 2001.

[10] Nuyttens D. Drift from field crop sprayers: the influence of spray application technology determined using indirect and direct drift assessment means. PhD disseratation. Leuven: Katholieke Universiteit, 2007; 293p.

[11] Spray Drift Task Force. A summary of ground application studies. Macon, Mo.: Stewart Agricultural Research Services, Inc.; 1997. Report No. 63552.

[12] Moon J, Lee D, Kang T, Yon K-S. A capacitive type of electrostatic spraying nozzle. J Electrostat, 2003; 57: 363–379.

[13] Law S E. Agricultural electrostatic spray application: a review of significant research and development during the 20th century. J Electrostat, 2001; 51–52: 25–42.

[14] Lenhardt T F. Agricultural liquid application nozzle, system and method. USA: United States Patent; US 6,276,617 B1, 2001.

[15] Zande J C van der, Butler Ellis C, Douzals J P, Stallinga H, Velde P Van, Michielsen JMGP. Spray drift reduction of the MagGrow spray system: Effect of magnetism, nozzle type, end nozzle and spray boom height. Wageningen, The Netherlands: Wageningen University and Research; 2017. Report No. 680.

[16] Maffei M E. Magnetic field effects on plant growth, development, and evolution. Front Plant Sci, 2014; 5: 1–15.

[17] Maheshwari B L, Grewal H S. Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. Agric Water Manag, 2009; 96: 1229–1236.

[18] Coey J M D, Cass S. Magnetic water treatment. J Magn Magn Mater, 2000; 209: 71–74.

[19] MagGrow. Website MagGrow [Internet]. 2019. Available from: http://www.maggrow.com Accessed on [2019-09-12]

[20] ASAE Standards. S572 AUG99: Spray nozzle classification by droplet spectra. 47th ed. St. Joseph, Mich. ASAE, 2000.

[21] ISO 22866. Equipment for crop protection — Methods for field measurement of spray drift. 1st ed. Geneva, Switzerland: International Organization for Standardization, Geneva, Switzerland; 2005. Report No. ISO 22866: 2005.

[22] Derksen R C, Paul P A, Zhu H. Field evaluations of application techniques for fungicide spray deposition on wheat and artificial targets. Appl Eng Agric, 2012; 28(3): 325–331.

[23] Hoffmann W C, Hewitt A J. Comparison of three imaging systems for water-sensitive papers. Appl Eng Agric, 2005; 21(6): 961–964.

[24] Huang Y, Thomson S J, Ortiz B V, Reddy K N, Ding W, Zablotowicz RM, et al. Airborne remote sensing assessment of the damage to cotton caused by spray drift from aerially applied glyphosate through spray deposition measurements. Biosyst Eng, 2010; 107: 212–220.

[25] Jamar L, Mostade O, Huyghebaert B, Pigeon O, Lateur M. Comparative performance of recycling tunnel and conventional sprayers using standard and drift-mitigating nozzles in dwarf apple orchards. Crop Prot, 2010; 29: 561–566.

[26] Zhu H, Salyani M, Fox R D. A portable scanning system for evaluation of spray deposit distribution. Comput Electron Agric, 2011; 76: 38–43.

[27] R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing, 2020.

[28] Bates D, Mächler M, Bolker B M, Walker S C. Fitting linear mixed-effects models using LME4. J Stat Softw, 2015; 67(1): 1–48.

[29] Gromping U. Relative importance for linear regression in R: The Package relaimpo. J Stat Softw, 2006; 17(1): 1–27.

[30] Mendiburu F D. agricolae: Statistical procedures for agricultural research. Journal of the American Statistical Association, 2017; 80(390): 486. doi: 10.2307/2287932.

[31] Wickham H, Chang W, RStudio. ggplot2: Create elegant data visualisations using the grammar of graphics. Springer-Verlag New York, 2016.

[32] Rimmer D A, Johnson P D, Kelsey A, Warren N D. Field experiments to assess approaches for spray drift incident investigation. Pest Manag Sci. 2009; 65: 665–671.

[33] Alves G S, Cunha da J P A R. Field data and prediction models of pesticide spray drift on coffee crop. Pesq agropec bras., 2014; 49(8): 622–629.

[34] Combellack J H, Western N, Richardson R. A comparison of the drift potential of a novel twin fluid nozzle with conventional low volume flat fan nozzles when using a range of adjuvants. Crop Prot., 1996; 15(2): 147–52.

[35] Ellis M C B, Alanis R, Lane A, Tuck C R, Nuyttens D, Gansberghelaan B Van. Spray drift : An investigation of the relationship between field , wind tunnel measurements and model predictions for determining drift reduction. Asp Appl Biol, 2016; 132: 207–216.

[36] Schampheleire M De, Baetens K, Nuyttens D, Spanoghe P. Spray drift measurements to evaluate the Belgian drift mitigation measures in field crops. Crop Prot, 2008; 27: 577–589.

[37] Piche M, Panneton B, Theriault R. Reduced drift from air-assisted spraying. Can Agric Eng, 2000; 42(3): 117–122.

[38] Wolf T M, Grover R, Wallace K, Shewchuk SR, Maybanks J. Effect of protective shields on drift and deposition characteristics of field sprayers. Can J Plant Sci, 1993; 73: 1261–1273.

[39] Phillips J C, Miller P C H. Field and wind tunnel measurements of the airborne spray volume downwind of single flat-fan nozzles. J agric Engng Res, 1999; 72: 161–170.

[40] Bayat A, Bozdogan N Y. An air-assisted spinning disc nozzle and its performance on spray deposition and reduction of drift potential. Crop Prot, 2005; 24: 951–960.

[41] Arvidsson T, Bergstrom L, Kreuger J. Spray drift as influenced by meteorological and technical factors. Pest Manag Sci, 2011; 67: 586–598.

[42] Baio F H R, Antuniassi U R, Castilho B R, Teodoro P E, Silva E E da. Factors affecting aerial spray drift in the Brazilian Cerrado. PLoS One, 2019; 14(2): 1–16.

[43] Ganzelmeier H, Rautmann D, Spangenberg R, Streloke M, Herrmann M, Wenzelburger HJ, et al. Studies on the spray drift of plant protection products. Berlin, Germany: Mitteilungen ausder Biologischen Bundesanstalt fu r Land- und Forstwirtschaft; 1995. 110p.

[44] Rockwell A D, Ayers P D. A variable rate, direct nozzle injection field sprayer. Appl Eng Agric, 1996; 12(5): 531–538.