Journal of Plant Protection Research ISSN 1427-4345

ORIGINAL ARTICLE

Forward angled spray: a method for improving the efficacy of herbicides

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Vol. 60, No. 3: 275–283, 2020

DOI: 10.24425/jppr.2020.133952

Received: March 11, 2020
Accepted: May 19, 2020

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Abstract

It is challenging to obtain proper leaf wetting. An angled spray could overcome this impediment, but which spray angle is best suited to droplet size is still unknown. In an outdoor pot experiment, seven doses of cycloxydim and sethoxydim were sprayed with single-orifice standard, anti-drift, and air induction (having a fine, medium, and extremely coarse spray quality, respectively) flat fan nozzles, using spray angles of 10°, 20° backward, 0° (vertical), 10°, 20°, 30°, 40°, 50°, and 60° forward relative to the direction of nozzle trajectory on wild barley at the three-leaf stage. Generally, the forward angled spray was better than the backward angled spray. With a standard flat fan nozzle, the forward angling of spray from 0° to 20° reduced the ED_{50} from 60.24 to 39.85 g a.i. · ha^{-1} for cycloxydim and from 150.51 to 81.13 g a.i. · ha^{-1} for sethoxydim. With an anti-drift flat fan nozzle, the forward angling of spray from 0° to 30° reduced the ED_{50} from 72.57 to 50.20 g a.i. · ha^{-1} for cycloxydim and from 181.94 to 104.51 g a.i. · ha^{-1} for sethoxydim. With an air induction flat fan nozzle, the forward angling of spray from 0° to 40° reduced the ED_{50} from 102.96 to 45.52 g a.i. · ha^{-1} for cycloxydim and from 209.91 to 92.80 g a.i. · ha^{-1} for sethoxydim. More angling did not improve the efficacy of these herbicides. Our results revealed that larger spray droplets needed more spray angle than smaller spray droplets to achieve an equal control.

Keywords: droplet size, grassy species, non-vertical spray, wild barley

Introduction

Eighteen post-emergence herbicides belonging to group A herbicides have been registered to date (WSSA 2010). They can inhibit the biosynthesis of fatty acids in the chloroplasts of grassy species by interfering with the acetyl-coenzyme A carboxylase activity, resulting in the disruption of cell growth and division, leading to plant death (Cobb and Reade 2010). Of this group, cycloxydim, sethoxydim, haloxyfop, and quizalofop are registered to control grassy weeds in canola in Iran. The first two herbicides at the recommended dose of the label (120 and 375 g · ha^{-1} for cycloxydim and sethoxydim, respectively) are effective to control wild barley (*Hordeum spontaneum* Koch.) (Aliverdi and Karami 2020), an annual winter grass found mainly in the Eastern Mediterranean, Middle East, Northern Asia, and Africa (Jakob *et al.* 2014). It is primarily a serious threat in wheat, causing yield loss of up to 75% at a density of 160 plants · m^{-2} (Hamidi and Mazaheri 2012). Since there is no suitable chemical management against wild barley in wheat, a wheat-canola rotation can make it possible for farmer to control it chemically in canola.

The inevitable application of group A herbicides has led to an increasing reliance of growers on them. As a result, different species have developed resistance to all herbicides in this group (Heap 2020). Therefore, optimizing their dosage should be considered as a way to reduce the strong selection pressure they exert on sensitive biotypes. The main goal in such an approach is to maximize the deposition of spray droplets on the target surface (i.e., weeds) (Jensen 2012). Optimization methods must be readily available and relatively inexpensive to meet growers' demands.

Generally, when the contact angle of the water droplet on the leaf surface is more than 110°, it means that the leaf surface is covered with crystalline epicuticular wax. In such a situation, the water droplet can be easily dislodged and run off the leaf surface (Knoche 1994). This is often true in grassy species and are referred to as hard-to-wet species (Hess and Foy 2000). Harr *et al.* (1991) reported that the contact angle of the water droplet with the leaf surface of wild barley is 180°. This has led us to conclude that wild barley is a hard-to-wet species. On such a species, the deposition of spray droplets is very strongly dependent on the surface tension of the spray solution (Knoche 1994). For this reason, the addition of a surfactant to the spray solution is a requirement for group A herbicides (Aliverdi *et al.* 2009).

At the three to four-leaf stage of grassy species (see wild barley in Fig. 1), when group A herbicides should be sprayed, the leaves are relatively perpendicularly oriented to the ground. So, when a single-orifice flat fan nozzle (e.g. standard, anti-drift, and air induction) is used to spray group A herbicides vertically, the spray droplets are most likely to strike non-perpendicularly to the leaf surface, resulting in a large proportion of them bouncing off the leaf surface onto the soil surface (endo-drift) (Jensen 2007). This is one reason for the hard wettability of grassy species (Jensen 2012). It has been established that the spray droplets of fungicides depositing on the leaves of *Triticum aestivum* L. can be improved by changing the spray angle from vertical to non-vertical, resulting in a large improvement of the efficacy of fungicides (Miller *et al.* 2002; Nicholson *et al.* 2003; Powell *et al.* 2004; Ozkan *et al.* 2012). Similar results were found for the deposition of fertilizer solution on *Hedera algeriensis* Hibberd. (Foqu´e and Nuyttens 2011) and a fluorescent tracer dye solution on artificial targets (Wolf and Peng 2011). However, few previous studies have considered the effect of angled spray on the efficacy of herbicides (Jensen 2007, 2012).

This study was aimed to investigate the effect of angled spray from three single-orifice flat fan nozzle types having different spray quality on the efficacy of cycloxydim and sethoxydim against wild barley.

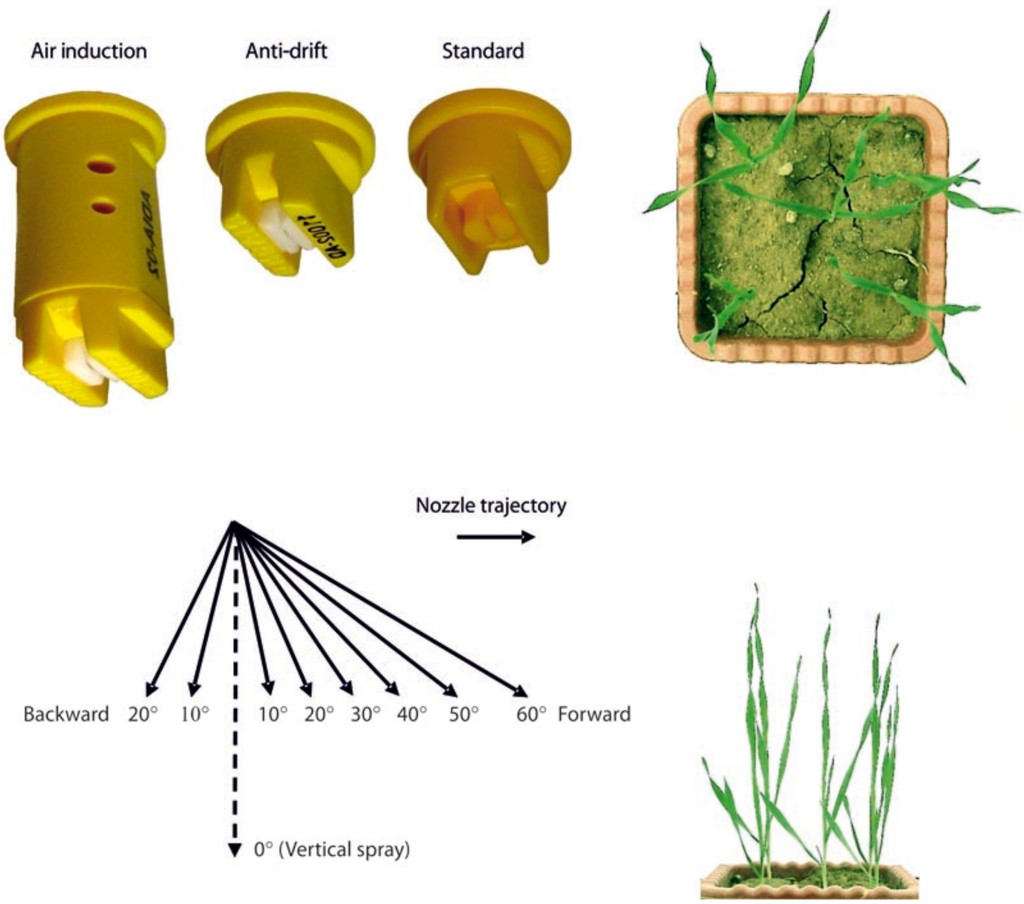

Fig. 1. Wild barley having vertically-oriented leaves at herbicide application time, the nozzles used in the study, and the angling of their spray from 20° backward to 60° forward relative to the direction of nozzle trajectory

Materials and Methods

Plant material and culture

In late June 2019, seeds of wild barley were collected from the experimental field situated at the Bu-Ali Sina University, Hamedan, Iran. The seeds were stored at 4°C in the dark until used. The experiment was conducted under outdoor conditions on the campus of Bu-Ali Sina University (34°79′22″N, 48°48′84″E, 1850 m asl) in 2019. Procedures to achieve uniform seedling emergence were: (1) the removal of lemma (not palea) from the seeds (Guoxiong *et al.* 2004), (2) the surface disinfection of seeds with 5% NaClO solution for 5 min, (3) the placement of seeds in 11 cm Petri dishes containing a layer of filter paper, (4) the addition of 15 ml of 0.2% KNO_3 solution to each Petri dish, (5) the storage of Petri dishes at 4°C in the dark for 48 h, (6) the storage of Petri dishes at room temperature in the dark for 48 h (Aliverdi and Karami 2020), (7) the transplantation of 10 seedlings with 1 cm coleoptile at 2 cm depth in each pot (17 × 17 × 20 cm) filled with 3 kg of a clay loam soil with 0.43% organic matter and a pH of 7.2, (8) the irrigation of pots once every 4 days, and (9) the thinning of the seedlings to five evenly sized ones at the one-leaf stage.

Experiments and treatments

With a 1-day interval, the experiment was performed twice (two runs). The first one was planted on 5 September 2019, sprayed on 27 September 2019 and harvested on 21 October 2019. In each run, two herbicides were tested, cycloxydim (Focus 10% emulsifiable concentrate, BASF, Germany) at seven doses of 0, 30, 45, 60, 90, 120, and 180 g a.i. $\cdot$ ha^{-1} and sethoxydim (Nabo-S 12.5% emulsifiable concentrate, BASF, Germany) at seven doses of 0, 93.7, 140.5, 187.5, 281.2, 375, and 562.5 g a.i. $\cdot$ ha^{-1}. Each of the doses was sprayed with three single-orifice standard, anti-drift, and air induction flat fan nozzle types (Table 1) using nine spray angles including 10° backward, 20° backward, 0° (vertical), 10° forward, 20° forward, 30° forward, 40° forward, 50° forward, and 60° forward relative to the direction of nozzle trajectory. For each herbicide in each experiment from each run, a randomized complete design with a 7 × 3 × 9 factorial arrangement of treatments using four factors (dose × nozzle type × spray angle) was conducted. There were four replicates of each treatment. The treatments were applied with a sprayer with 230 l $\cdot$ ha^{-1} spray volume at 300 kPa spray pressure, 50 cm above the plants. Wild barley was at the three-leaf stage (Fig. 1). Air temperature and relative humidity were 18 ± 4°C and 65 ± 10%, respectively. In each run, the plants in the four pots (which were additionally included) were harvested from the soil surface on the day of spraying, oven-dried at 70°C for 48 h, and weighed (Result = 0.17 g $\cdot$ plant^{-1}).

Data collection and analysis

Three weeks after treatment, the treated plants in each pot were harvested from the soil surface, oven-dried at 70°C for 48 h and weighed. The obtained data were divided into five (plants $\cdot$ pot^{-1}) and then subtracted from 0.17 (dry weight on the day of spraying). Then, the data were subjected to analysis of variance using SAS software. A normal distribution of data was stabilized (Shapiro-Wilk test > 0.90). No significant run-by-treatment interactions occurred. Hence, the data were pooled to give eight replications and then subjected to a non-linear regression analysis over herbicide dose using the *drc* package in R software version 2.1.0 (Ritz *et al.* 2015). A four-parameter log-logistic model, $Y = c + \{d - c/1 + \exp[b(\log x - \log ED_{50})]\}$, was recognized to be valid (Lack-of-Fit test > 0.05). Here, d and c are upper and lower limits for Y, respectively; ED_{50} is effective dose that gives a 50% reduction in dry weight between the d and c; and b is the slope of the curve around ED_{50}. The separation of the ED_{50} within each herbicide was performed by the standard errors at the 5% significance level (Knezevic *et al.* 2010).

Results and Discussion

For each herbicide, the dose–response curves were similar in all parameters (b, d, and c) except for ED_{50}. The b parameter ranged from 3.17 ± 0.46 to 4.29 ± 0.66 in cycloxydim and from 3.01 ± 0.51 to 4.12 ± 0.83

Table 1. Details for nozzles used in the study, all with 11002 at 300 kPa

Nozzle type	Spray geometry	VMD range [μm]	Droplet category	Manufacturer
Standard	single flat fan	114–235	fine	AgroTop, Germany
Anti-drift	single flat fan	236–340	medium	MagnoJet, Brazil
Air induction	single flat fan	503–665	extremely coarse	MagnoJet, Brazil

VMD – Volume Median Diameter

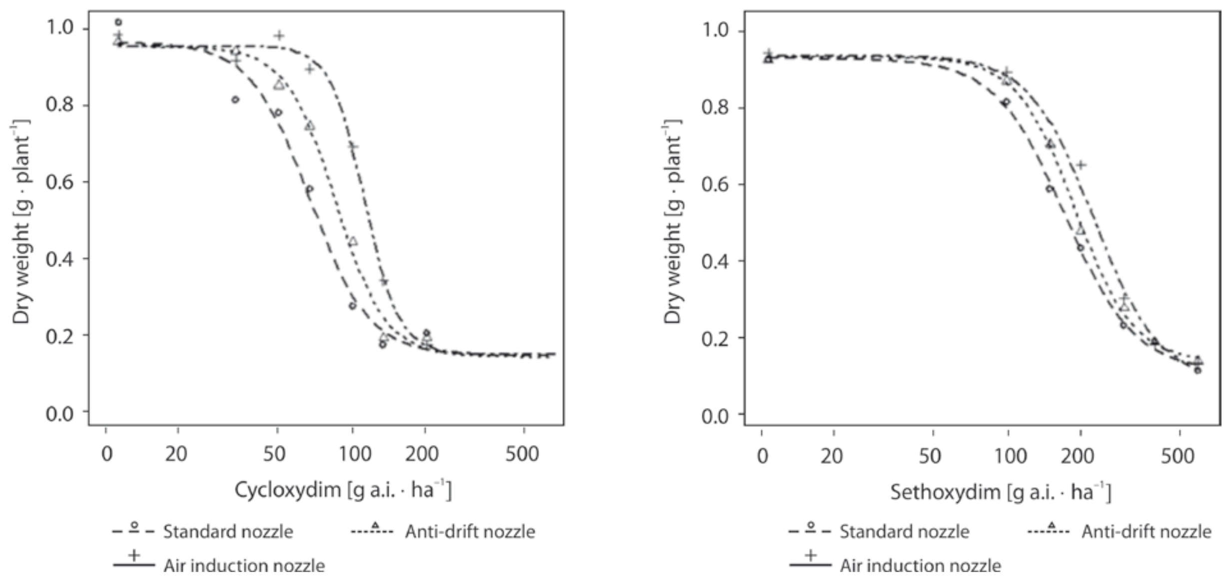

Fig. 2. Response of wild barley dry weight to doses of cycloxydim and sethoxydim sprayed vertically using standard (○), anti-drift (Δ) and air induction (+) flat fan nozzles. Data points are means of eight replicates from two experiments

in sethoxydim. For both herbicides, the *d* parameter ranged from 0.93 ± 0.03 to 0.96 ± 0.05 and the *c* parameter ranged from 0.12 ± 0.02 to 0.14 ± 0.03. In such a situation, the dose-response curves can be regarded as being parallel (Ritz *et al.* 2006). As a result, the relative potency (*R*), signifying the horizontal displacement between the two dose-response curves, can be calculated. It is described as $R = ED_{50\ \text{vertical spray}} / ED_{50\ \text{non-vertical spray}}$. According to this definition, when the *R* is >1, the efficacy of the herbicide is improved with the non-vertical spray of nozzle. Whereas, when the *R* is <1, the reverse is true.

The estimated ED_{50} values for all dose-response curves are reported in Table 2. Based on the ED_{50} values of herbicides in Table 2, they were affected by nozzle type. When the herbicides were vertically sprayed (Fig. 2), the ED_{50} values for cycloxydim spraying with standard, anti-drift, and air induction flat fan nozzles were 60.24, 72.57, and 102.96 g a.i. · ha^{-1}, respectively. These values for sethoxydim were 150.51, 181.94, and 209.91 g a.i. · ha^{-1}, respectively. These results showed that the ED_{50} values for both herbicides were as standard < anti-drift < air induction flat fan nozzles. These results relate to the differences in the droplet size produced by different types of nozzles (Table 1). As such, a negative relation between the size of spray droplets and the efficacy of the herbicide was observed. This led us to conclude that the larger the droplet size, the more the spray endo-drift. A 41.5 and 28.3% reduction in the efficacy of cycloxydim and sethoxydim occurred when the quality of spray droplets changed from fine with a standard flat fan nozzle to extremely coarse with an air induction flat fan nozzle, respectively. Studies have established that the efficacy of group A herbicides against hard-to-wet species increased when the droplet size decreased. Examples of this are: diclofop-methyl on *Avena fatua* (Scoresby and Nalewaja 1984), fluazifop-P-butyl on *Agropyron repens* (L.) Beauv. (Chandrasena and Sagar 1989), haloxyfop-ethoxyethyl, fluazifop-P-butyl on *Lolium perenne* L. (Jensen 2007, 2012), clodinafop-propargyl, sethoxydim on *Avena sterilis* ssp. *ludoviciana* Durieu. (Aliverdi and Ahmadvand 2018; Aliverdi 2018) and cycloxydim on *Hordeum spontaneum* Koch. (Aliverdi and Karami 2020). This is also true for other groups (mode of actions) of herbicides against easy-to-wet species (Knoche 1994; Huang *et al.* 2000; Shaw *et al.* 2000; Sasaki *et al.* 2013; Creech *et al.* 2015; Meyer *et al.* 2016). Due to a low level of energy existing in smaller spray droplets, they can easily be deposited on the leaf surface, leading to greater efficacy of the herbicide (Penner 2000). Of course, this is true when wind speed is low. Under high wind speed, smaller spray droplets can easily drift, leading to a lower deposition and efficacy of the herbicide.

The efficacy of cycloxydim and sethoxydim was affected by the spray angle of the nozzle, depending mainly on the nozzle type (Table 2). In comparison to vertical spray, none of the backward angled sprays affected the efficacy of spraying both herbicides with a standard flat fan nozzle. With an anti-drift flat fan nozzle (only 20° backward angled spray) and with an air induction flat fan nozzle (both 10 and 20° backward angled sprays), there was increased efficacy of both herbicides. This finding might indicate that by increasing the size of spray droplets, the backward angled spray improved the efficacy of the herbicide In other words, larger spray droplets need a more backward spray angle for better deposition on wild barley than smaller spray droplets. Of course, it should be noted, that two backward angled sprays tested in this study are not enough to support this conclusion. Already, 10, 30, 45, and 60° backward angled sprays have been investigated by Jensen (2007) who showed that the efficacy of haloxyfop-ethoxyethyl spraying with a 110015 anti-drift flat fan nozzle and a 11002 standard flat fan nozzle on *L. perenne* steadily increased by increasing the nozzle angle.

With a standard flat fan nozzle, 10° forward angled spray (ED_{50} = 61.16 g a.i. · ha^{-1}) did not affect the efficacy of cycloxydim on wild barley when compared to vertical spray (ED_{50} = 60.24 g a.i. · ha^{-1}). However, this treatment increased the efficacy of sethoxydim by 1.24-fold. With an anti-drift flat fan nozzle, 10° forward angled spray increased the efficacy of cycloxydim and sethoxydim by 1.17- and 1.33-fold, respectively. With an air induction flat fan nozzle, 10° forward angled spray increased the efficacy of cycloxydim and sethoxydim by 1.34- and 1.49-fold, respectively. Comparing the results of other forward angled sprays (Table 2), we concluded that changing the spray angle can be more suitable for larger spray droplets. It has been shown that a 13° forward angled spray with a 11002 air induction flat fan nozzle can increase the efficacy of sethoxydim on *A. sterilis* ssp. *ludoviciana* Durieu. by 1.18-fold compared to a vertical spray (Aliverdi 2018).

Except in the case of spraying cycloxydim with a standard flat fan nozzle, the ED_{50} values for spraying both herbicides with a 10° forward angled spray were lower than that with a 10° backward angled

Table 2. The effect of nozzle type and spray angling on the dose of cycloxydim or sethoxydim required for 50% reduction in dry weight of wild barley

Nozzle type	Spray angling	Cycloxydim		Sethoxydim	
		ED_{50} [g a.i. · ha^{-1}]	relative potency	ED_{50} [g a.i. · ha^{-1}]	relative potency
Standard	Vertical	60.24 (4.57) e	1.00	150.51 (9.94) ef	1.00
	20° backward	62.21 (3.51) e	0.97	132.85 (7.11) de	1.13
	10° backward	58.01 (4.68) de	1.04	156.54 (7.35) f	0.96
	10° forward	61.16 (4.50) e	0.98	121.64 (8.25) d	1.24
	20° forward	39.85 (1.85) a	1.51	81.13 (6.71) a	1.86
	30° forward	41.96 (2.70) ab	1.44	87.91 (4.26) ab	1.71
	40° forward	41.19 (1.31) ab	1.46	89.46 (3.29) ab	1.68
	50° forward	41.35 (2.24) ab	1.45	83.38 (2.60) a	1.81
	60° forward	43.24 (0.63) b	1.39	94.10 (1.57) b	1.60
Anti-drift	Vertical	72.57 (3.89) f	1.00	181.94 (12.72) g	1.00
	20° backward	65.91 (2.00) e	1.10	143.80 (11.07) ef	1.27
	10° backward	74.62 (3.11) fg	0.91	188.15 (7.39) gh	0.97
	10° forward	61.63 (2.24) e	1.17	137.07 (9.10) de	1.33
	20° forward	50.20 (4.43) d	1.44	104.51 (6.06) c	1.74
	30° forward	42.76 (2.11) ab	1.70	86.90 (5.28) ab	2.09
	40° forward	41.72 (2.48) ab	1.74	86.31 (6.20) ab	2.11
	50° forward	43.61 (1.20) b	1.66	92.03 (3.01) b	1.98
	60° forward	43.04 (1.33) b	1.69	91.59 (5.11) ab	1.99
Air induction	Vertical	102.96 (3.96) i	1.00	209.91 (14.91) h	1.00
	20° backward	83.33 (2.58) g	1.20	162.04 (9.22) f	1.30
	10° backward	91.15 (4.02) h	1.10	180.78 (6.90) g	1.16
	10° forward	74.54 (8.65) fg	1.34	141.34 (6.62) e	1.49
	20° forward	61.76 (5.28) e	1.62	134.40 (13.19) de	1.56
	30° forward	54.89 (3.76) de	1.82	112.22 (5.40) c	1.87
	40° forward	45.52 (3.28) b	2.26	92.80 (8.19) b	2.26
	50° forward	44.61 (4.09) ab	2.24	93.53 (5.49) b	2.23
	60° forward	46.94 (1.96) b	2.13	103.36 (4.24) b	2.03

Standard errors are in parentheses. The ED_{50} values with the same letter are not different ($p < 0.05$). For each nozzle type, the relative potency values are calculated by dividing the value of ED_{50} with vertical spray by the value of ED_{50} with each non-vertical spray

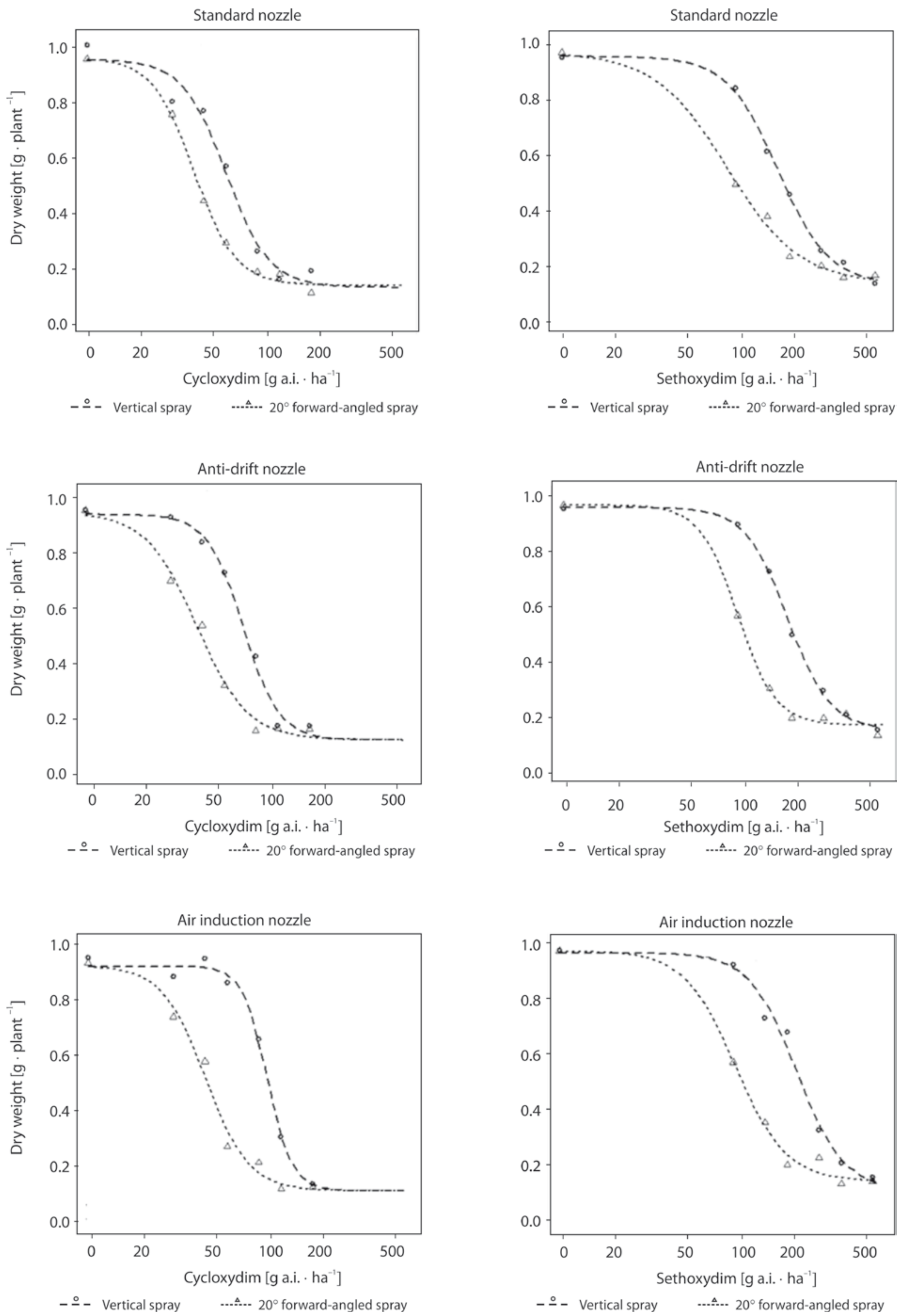

Fig. 3. Response of wild barley dry weight to doses of cycloxydim and sethoxydim sprayed vertically (○) and the minimum spray angle causing the best herbicide efficacy (Δ); 20° forward-angled spray with a standard nozzle, 30° forward-angled spray with an anti-drift nozzle, and 40° forward-angled spray with an air induction nozzle. Data points are means of eight replicates from two experiments

spray. Such an advantage of forward angled spray over a backward angled spray was also observed by changing the angle to 20°. A similar result was reported by Jensen (2007 and 2012). It seems that forward angled spray can propel the droplets in a more appropriate direction to strike the leaf surface than a backward angled spray.

With a standard flat fan nozzle, the forward angling of spray from 10 to 20° resulted in a reduction in the ED_{50} values of cycloxydim from 61.16 to 39.85 g a.i. · ha^{-1} and sethoxydim from 121.64 to 81.13 g a.i. · ha^{-1}. For both herbicides, there was no difference in the ED_{50} values with the forward angled sprays of 20 to 50°. The dose-response curve of vertical spray angle and the minimum spray angle causing the best herbicide efficacy (20° forward-angled spray) are shown in Figure 3. Using a 20 to 50° forward angled spray improved the efficacy of cycloxydim and sethoxydim by about 1.5 and 1.8-fold as compared to vertical spray, respectively. However, the forward angling of spray from 50 to 60° resulted in an increase in the ED_{50} values of cycloxydim from 41.35 to 43.24 g a.i. · ha^{-1} and sethoxydim from 83.38 to 94.10 g a.i. · ha^{-1} (Table 2). With an anti-drift flat fan nozzle, the forward angling of spray from 10 to 30° resulted in a continuous reduction in the ED_{50} values of cycloxydim from 61.63 to 50.20 g a.i. · ha^{-1} and sethoxydim from 137.07 to 104.51 g a.i. · ha^{-1}. In both herbicides, there was no difference in the ED_{50} values with the forward angled sprays of 30 to 60°. The dose-response curve of vertical spray angle and the minimum spray angle causing the best herbicide efficacy (30° forward-angled spray) are shown in Figure 3. Using a 30 to 60° forward angled spray improved the efficacy of cycloxydim and sethoxydim by about 1.7 and 2.0-fold as compared to vertical spray, respectively (Table 2). With an air induction flat fan nozzle, the forward angling of spray from 10 to 40° resulted in a continuous reduction in the ED_{50} values of cycloxydim from 74.54 to 45.52 g a.i. · ha^{-1} and sethoxydim from 141.34 to 92.80 g a.i. · ha^{-1}. In both herbicides, there was no difference in the ED_{50} values with the forward angled sprays of 40 to 60°. The dose-response curve of vertical spray angle and the minimum spray angle causing the best herbicide efficacy (40° forward-angled spray) are shown in Figure 3. Using a 40 to 60° forward angled spray improved the efficacy of both herbicides by about 2.2-fold as compared to vertical spray, respectively (Table 2). These findings might support our previous assumption about backward angled spray. Again, larger spray droplets need more forward spray angle for better deposition on wild barley than smaller spray droplets. Although Jensen (2007) tested different nozzle sizes, he reported that a 45° forward angled spray with a 11002 standard flat fan nozzle having a fine spray quality and a 60° forward angled spray with a 110015 anti-drift flat fan nozzle having a medium spray quality are the best anglings to spray haloxyfop ethoxyethyl on *L. perenne*. Wolf and Peng (2011) sprayed a fluorescent tracer dye solution on artificial vertically and horizontally-oriented targets and reported that the angling of spray can increase the spray deposition on a vertical target, but not on a horizontal target. Presumably, this is a possible reason that the efficacy of ioxynil + bromoxynil was not affected by nozzle angling on *Brassica napus* L., a broadleaved species having horizontally oriented leaves (Jensen 2012). In contrast, an increase in spray deposition on grassy species having vertically oriented leaves by an angled spray can cause a large improvement of the efficacy of fungicides (Miller *et al.* 2002; Nicholson *et al.* 2003; Powell *et al.* 2004; Ozkan *et al.* 2012), fertilizers (Foqu´e and Nuyttens 2011), and herbicides (Jensen 2007, 2012). It is clear that only two studies have documented the effect of angled spray on the efficacy of herbicides. However, nozzle manufactures have paid much attention to this issue because some types of nozzles recommended by them to apply herbicides can provide a forward angled spray such as a compact fan air-tilt nozzle with a 13° forward angled spray (ASJ 2018), guardian air flat fan nozzle with a 20° forward angled spray (Hypro 2013), tilt 30 flat fan nozzle with a 30° forward angled spray (ASJ 2018), defy 3D nozzle with a 30° forward angled spray (Syngenta 2020), super turbo flat fan nozzle and air induction super turbo flat fan nozzle with a 30° forward angled spray (MagnoJet 2015).

As mentioned above, when the herbicides were vertically sprayed using three nozzle types, a negative relation between the size of spray droplet and the efficacy of the herbicide was observed. The results showed that this relation can be neutralized with an angled spray if a spray angle is provided with increased spray droplet size. For example, there was no difference among the ED_{50} values obtained from a standard flat fan nozzle spraying with 20° forward angled spray (39.85 g a.i. · ha^{-1}), anti-drift flat fan nozzle spraying with 30° forward angled spray (42.76 g a.i. · ha^{-1}), and an air induction flat fan nozzle spraying with 40° forward angled spray (44.61 g a.i. · ha^{-1}). These findings are in agreement with Jensen (2012) who reported that there were no differences among the ED_{50} for clodinafop-propargyl spraying with standard, anti-drift, and air induction flat fan nozzles (having fine, medium, and coarse spray quality, respectively) using a 60° forward angled spray on *L. perenne*.

Conclusions

A method to minimize the endo-drift of group A herbicides, leading to an increased efficacy of them is a forward angled spray. This method was more advantageous for larger spray droplets than for smaller spray droplets. To obtain a maximum advantage of this method, larger spray droplets need more spray angle for better deposition on vertically oriented leaves than smaller spray droplets. Although it is common knowledge that the efficacy of post-emergence herbicides increased as the droplet size increased, it is not true when a forward angled spray is applied.

Acknowledgements

This work was funded by a grant from the Bu-Ali Sina University. No conflicts of interest have been declared.

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