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THE OUTLET DESIGN OF FLAT FAN NOZZLE VARIES THE APPLICATION TIME OF DAY EFFECT ON NICOSULFURON ACTIVITY

Akbar Aliverdi[1], Abolfazl Aliverdi[2], Jason Connor Ferguson[3]

[1]Department of Agronomy and Plant Breeding, Faculty of Agriculture, Bu-Ali Sina University, Shahid Mostafa Ahmadi Roshan St., Hamedan, 6516738695, Islamic Republic of Iran
[2]Department of Horticulture, Faculty of Agriculture, Bu-Ali Sina University, Shahid Mostafa Ahmadi Roshan St., Hamedan, 6516738695, Islamic Republic of Iran
[3]Department of Plant and Soil Sciences, College of Agricultural and Life Sciences, Mississippi State University, 32 Creelman St, Mississippi State, MS 39762, United States of America

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Vastutav autor: Corresponding author: Akbar Aliverdi

E-mail: a.aliverdi@basu.ac.ir

ORCID:
0000-0002-0209-4755 (AkA)
0000-0002-7737-5420 (AbA)
0000-0003-4690-1288 (JCF)

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ABSTRACT. On two container-grown species, johnsongrass and velvetleaf, nicosulfuron was sprayed with the Anti-Drift Single, Dual, and Triplet Flat-Fan nozzles (AD/S, AD/D, AD/T nozzles, respectively) at 05:00 to 21:00, with a two-hour interval. At 5:00 to 11:00, nicosulfuron activity on both species was greatest with the AD/T followed by the AD/D and finally, the AD/S nozzle. At 15:00 to 19:00, however, nicosulfuron activity on johnsongrass was greatest with the AD/D, followed by the AD/T and finally, the AD/S nozzle, and nicosulfuron activity on velvetleaf was greatest with the AD/D followed by the AD/S and the AD/T nozzle had the lowest control. Nicosulfuron applied with the AD/T nozzle in the early morning caused the highest desiccation (70%) in both species. The best time to apply nicosulfuron was in the early morning. However, velvetleaf undergoes foliar nyctinasty depending on daylight, which made effective control achieved by only the AD/D and AD/T nozzles.

Introduction

Nicosulfuron is a postemergence herbicide that is used in corn (*Zea mays* L.) to control many monocotyledonous weeds, *e.g*. johnsongrass (*Sorghum halepense*) which is a perennial plant, and dicotyledonous weeds, *e.g.* velvetleaf (*Abutilon theophrasti*) which is an annual plant, (Dobbels, Kapusta, 1993). It belongs to the enzyme acetolactate synthase (ALS)-inhibiting herbicide group (B/2). In the chloroplast, ALS biosynthesizes some essential amino acids (isoleucine, leucine, and valine). If ALS is inactivated, cell division stops; and eventually, plant death occurs (Cobb, Reade, 2010).

The slow degradation of nicosulfuron causes carryover effects on succeeding crops, *e.g*., cabbage, onion (Greenland, 2003), and potato (Novo, Miranda-Filho, 2006). On the other hand, it can exert the extreme selection pressure against the susceptible biotypes, causing the evolution of nicosulfuron resistance in 26 different weed species worldwide. In the meantime, nicosulfuron resistance has been reported in johnsongrass but not in velvetleaf (Heap, 2020). If nicosulfuron is used rationally, the spray droplets can be delivered the target effectively. Herbicide rational application has three essential elements: herbicide selectivity, appropriately timed application, and application accuracy (Aliverdi, Karami, 2020).

Previous study reported that nicosulfuron activity to control barnyard grass (*Echinochloa crus-galli*) depends on the application time of day (Stewart *et al*., 2009). They said that nicosulfuron was more effective when it has been applied in the early morning than other times of day. The dependence of herbicide activity on the time of day has been termed as the application time of day effect evidencing in two other ALS herbicides included imazapic and imazethapyr (Stopps *et al*., 2013; Carter, Prostko, 2019). In general, the review of this literature revealed that the highest activity of contact herbicides is achieved when they have been used in the nighttime, especially after sunset. The greatest activity of systemic herbicides is achieved when they have been used in the daytime. Moreover, the review of this literature revealed that all herbicides mentioned above had been sprayed by a single flat-fan nozzle. In addition, there are two other designs in the market, including dual and triplet flat-fan nozzles. In previous study conducted at a specific time of day, the highest control of weed was achieved when clodinafop-propargyl has applied with AD/D nozzle as compared to AD/S nozzles (Aliverdi, Karami, 2020) but in another study, the highest control of weed was achieved when cycloxydim has applied with triplet flat fan nozzles compared to dual flat fan nozzles (Aliverdi, Karami, 2020). The triplet flat fan nozzle has recently released by the MagnoJet company in Brazil since 2014 and is newer than the single and dual flat-fan nozzles.

This experiment aims to specify the best time(s) of day for applying nicosulfuron using the AD/S, AD/D, and AD/T nozzles. Two weeds species, one broadleaf species – velvetleaf and one grass species – johnsongrass, which differs in their leaf angle at different times of day, were used in this study.

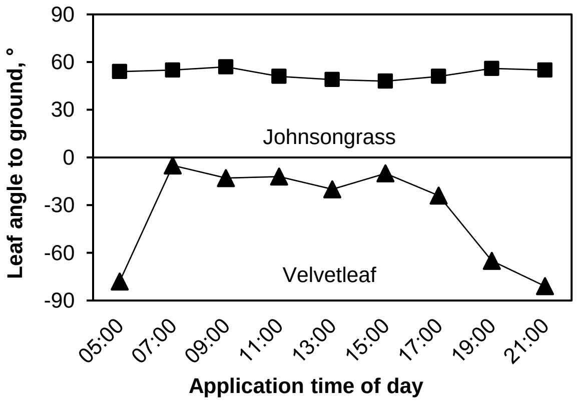
Materials and Methods

The seeds of johnsongrass and velvetleaf were collected from Hamedan and Gorgan fields, Iran, in the summer of 2018, respectively. They were stored in the laboratory until the beginning of the study conducting in the Bu-Ali Sina University, Hamadan, Iran from May to August 2019.

To break dormancy, johnsongrass seeds were immersed in concentrated sulfuric acid for 3 min (Parsa *et al*., 2013), and velvetleaf seeds were immersed for 1 hour in 60 °C water (Ravlić *et al*., 2015). Then, they were washed with cold water. Approximately 10 treated seeds of each weed species were planted at 0.5 cm soil depth in 2 L containers containing clay loam soil with 0.7% organic matter and 7.2 pH. The containers were placed in outdoor conditions. The soil surface of containers was kept continuously moist for up to a week. After the emergence of seedlings, they were thinned to maintain 4 seedlings container^{-1} and irrigated equally every two days with tap water.

For each weed species, a two-factor experiment (3 × 9) was conducted as a completely randomized design. For each treatment, there were four replications. With a one-day interval, the experiment was repeated at all stages. The 1st run was planted on 30 May 2019, sprayed on 11 July 2019, and harvested on 2 August 2019. The 2nd run was done with one-day interval after the first experimental ones. The 1st factor was the nozzle outlet design including the AD/S, AD/D, and AD/T nozzles, all types were 11002VK; and the 2nd factor was application time of day including 05:00, 07:00, 09:00, 11:00, 13:00, 15:00, 17:00, 19:00, and 21:00. Sunrise and sunset occurred at 06:10 and 20:32, respectively.

For each weed species, four unsprayed containers (untreated control) were considered for comparison purposes. In the four-leaf stage, both weed species were treated with the recommended dose of nicosulfuron, 80 g a.i. ha^{-1} (Cruz®, SC 4%, Alborz Behsam, Iran), using an a compressed-air sprayer (Solo 461 model, Germany) calibrated to deliver 210 L ha^{-1} at 300 kPa. Before applying the herbicide at different times of day, the angle of the fourth leaf of the plants inside the containers to the ground was measured, then averaged, and showed in Fig. 1. The leaf angle of 0° means it has horizontal status, the leaf angle less than 0° means it is oriented downward, the leaf angle more than 0° means it is oriented upward, and the leaf angle of 90° or –90° means it is parallel to the stem. Moreover, air properties at the application times were measured and showed in Figure 1. According to the nozzles manual (MagnoJet, 2020), the size of the droplets at 300 kPa for the AD/S and AD/D nozzles ranged from 236 to 340 µm and for the AD/T nozzle ranged 106-235 µm. In the AD/D and AD/T nozzles, the angle between the two flat fans is 40°.



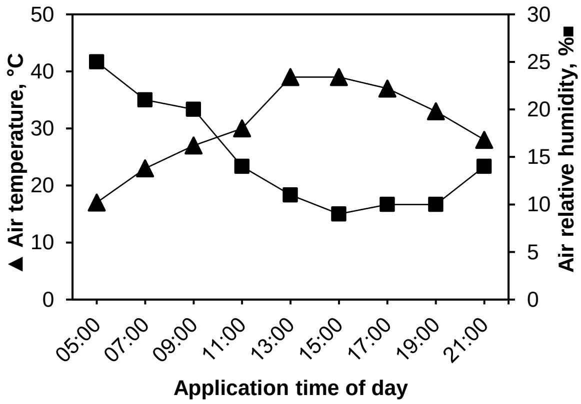


Figure 1. The fourth leaf angle of johnsongrass and velvetleaf (top), air temperature and relative humidity (down) at different times of day. Data are means of two continuous days

Twenty days after spraying, the plant biomass were removed at the soil surface. The fresh weight (FW) and dry weight (DW) of each experimental unit (container) were obtained and divided by 4 (number plant container $^{-1}$). Finally, the ratio of FW/DW was used in statistical analysis. The ratio of FW/DW has a starting range from one and up and shows the intensity of dehydration in tissues due to herbicide action. A FW/DW ratio close to one means dehydration completely (Rytwo, Tropp, 2001). The data had a normal distribution confirming the Shapiro-Wilk test more than 0.90. Then, the data were subjected to analysis of variance (ANOVA) using SAS software. No significant run-by-treatment interactions occurred. Hence, the data were pooled to give eight replications, then re-analyzed. For mean separations, Duncan's multiple range test was used at a 0.05 probability level.

Results

The ratio of FW/DW for johnsongrass and velvetleaf non-treated with nicosulfuron (control) were 7.3 and 6.8, respectively. All of the herbicide treatments reduced the ratio of FW/DW in both weed species. Hereafter, this reduction was expressed as a dehydration percentage. ANOVA showed that nozzle outlet design and application time of day significantly affected the ratio of FW/DW for johnsongrass and velvetleaf. The two-way interaction was also significant in both weed species. In johnsongrass, the lowest activity of nicosulfuron was observed when it was applied with the AD/S nozzle from 13:00 to 19:00 (49.5 to 53.6% dehydration). While, the highest activity of nicosulfuron was achieved when it was applied with the AD/T nozzle at 5:00 (73.6% dehydration) and 7:00 (72.3% dehydration) (Fig. 2). In velvetleaf, the lowest activity of nicosulfuron was observed when it was applied with the AD/S nozzle at 19:00 (43.5% dehydration) and 21:00 (42.2% dehydration). While, the highest activity of nicosulfuron was achieved when it was applied with the AD/T nozzle from 5:00 to 9:00 (69.1 to 72.1% dehydration) (Fig. 2).

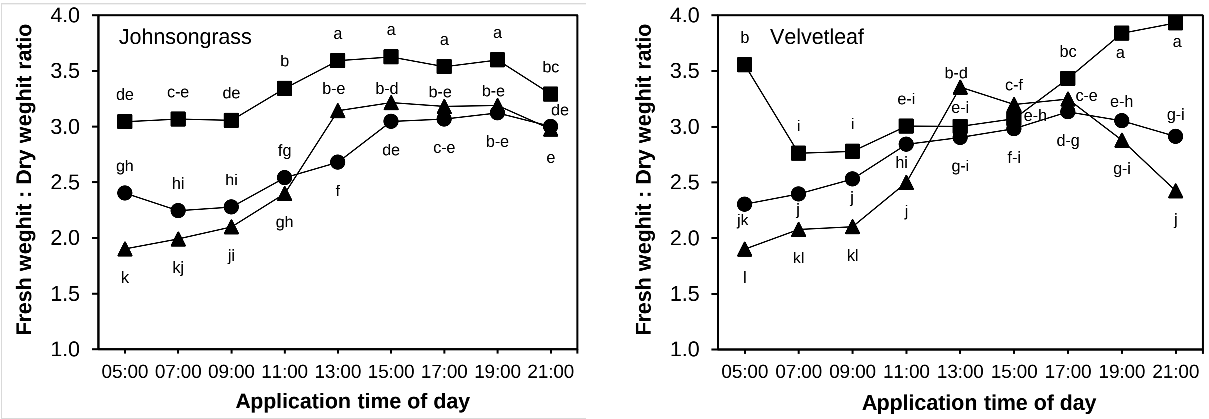


Figure 2. Fresh weight: dry weight ratio of johnsongrass (top) and velvetleaf (down) treated with nicosulfuron, which have sprayed with the anti-drift single (■), dual (●), and triplet flat-fan nozzles (▲) at different times of day. The means followed by same letter are not significantly different according to Duncan's multiple range test at the 5% probability level. Data are means of eight replicates from two runs.

At all application times of day, the use of AD/D nozzle significantly caused more dehydration in johnsongrass than the AD/S nozzle. Two non-vertical sprays created by the AD/D nozzle (one with 40° forward and another with 40° backward to the direction of nozzle trajectory) can increase the possibility of the deposition of droplets on the front and back side of monocotyledonous plants, resulting in improved activity of nicosulfuron. This finding also supports previous study (Jensen, 2012). At 5:00 and 9:00, the activity of nicosulfuron with the AD/T nozzle was higher than that with the AD/D nozzle. Conversely, at 13:00, the activity of nicosulfuron with the AD/D nozzle was higher than that with the AD/T nozzle.

Similar to the trend observed for johnsongrass, the trend of changes in the FW/DW ratio for velvetleaf over different application times of day showed that in the AD/D and AD/T nozzles, the FW/DW ratio in the early morning applications (5:00 to 9:00) are lower than in the afternoon applications (13:00 to 19:00). However, the trend of these changes in the AD/S nozzle differed from those in the AD/D and AD/T nozzles (Fig. 2) and it was correlated negatively with the trend of changes in the leaf angle of velvetleaf over different times of day (Fig. 1). When nicosulfuron was applied with the AD/S, AD/D, and AD/T nozzles at 5:00, the intensity of dehydration in tissues of velvetleaf was 47.7, 66.2, and 72.1%, respectively.

Discussion

In general, the trend of changes in the FW/DW ratio of johnsongrass over different times of day showed that in each nozzle outlet design, the FW/DW ratio in the early morning applications (5:00 to 9:00) are lower than in the afternoon applications (13:00 to 19:00). These results indicate that with each nozzle outlet design, the best time(s) to apply nicosulfuron was in the early morning. In contrast, the worst time(s) to apply nicosulfuron was in the afternoon. This result might be related to differences in air properties at application times of day (Fig. 1). Stewart *et al*. (2009), who used nicosulfuron in Ontario, Canada to control barnyard grass with a single flat fan nozzle at different times of day, also identified in the early morning applications as the highest nicosulfuron activity. They stated that the spray droplets dry faster in the noon and afternoon applications due to high air temperatures and low relative humidity, leading to faster crystallization of the active ingredient of herbicide, resulting in decreased absorption and activity of nicosulfuron. Other studies have shown that the absorption of paraquat, fomesafen, and glufosinate (Preston *et al*., 2005; Cieslik *et al*., 2014; Ramsey *et al*., 2002) has decreased with increasing air temperature and decreasing air relative humidity. Decreased herbicide absorption is due to the faster crystallization of the active ingredient of the herbicides. However, the afternoon applications of atrazine, imazethapyr, and glyphosate (Stopps *et al*., 2013; Mohr *et al*., 2007) were the best time of day. Moreover, the noon applications of bromoxynil and 2,4-D (Stewart *et al*., 2009; Montgomery *et al*., 2017) were the best time of day.

At all times of nicosulfuron application of day, the use of AD/D nozzle significantly caused more dehydration in johnsongrass than the AD/S nozzle. The leaves of monocotyledonous weeds, such as johnsongrass, are relatively upright (perpendicular to the ground) throughout the day (Fig. 1). On the other hand, with the AD/S nozzle, the spray droplets fall perpendicularly. Therefore, the spray droplets mainly hit the leaf surface obliquely. As a result, they are more likely to bounce off from the leaf surface to the ground and be endo-drifted. In a previous study, improved activity of some graminicides by changing the spray angle of a single flat fan nozzle from vertical to non-vertical has been reported (Jensen, 2012). In the current study, two non-vertical sprays created by the AD/D nozzle (one with 40° forward and another with 40° backward to the direction of nozzle trajectory) can increase the possibility of the deposition of spray droplets on the leaves of monocotyledonous weeds, resulting in improved activity of nicosulfuron. The higher performance of AD/D nozzle than AD/S nozzle (Aliverdi, Karami, 2020) has already reported.

In the early morning and morning applications, the activity of nicosulfuron with the AD/T nozzle was higher than that with the AD/D nozzle. Conversely, in the afternoon applications, the activity of nicosulfuron with the AD/D nozzle was higher than that with the AD/T nozzle. This finding might be related to differences in the spray droplet size produced by these types of nozzles. The AD/T nozzle has finer spray droplets than the AD/D nozzle (MagnoJet, 2020). The smaller the size of the spray droplets, the more their retention on the target (Ferguson *et al*., 2018). Therefore, it can be inferred from the results that in afternoon applications under the higher air temperature and the lower relative humidity conditions, the finer spray droplets produced by AD/T nozzle, although they deposit in a greater volume on the target, can evaporate faster, resulting in decreased activity of nicosulfuron in the afternoon applications. With decreasing the leaf angle of velvetleaf, the FW/DW ratio of velvetleaf increased. In other words, the more the leaf is oriented downward, the lower the leaf is dehydrated. Unlike johnsongrass, velvetleaf showed a strong leaf nyctinasty depending on daylight (Fig. 3).

5:00

7:00

Figure 3. Foliar nyctinasty in velvetleaf depending on daylight. Sunrise at 06:10

In previous studies in which herbicides have been sprayed with a single flat fan nozzle causing a perpendicular movement of spray droplets to the ground, the researchers have found that the leaf nyctinasty in weeds decreases the deposition of spray droplets on the leaf surface, resulting in decreased activity of herbicide (Sellers *et al*., 2003). For example, the leaf angle of velvetleaf at 14:00, 17:00, 18:30, 19:15, and 20:00 in the study of Mohr *et al*. (2007) was –10, –10, –30, –60 and –80° respectively. They reported that with reducing the leaf angle of velvetleaf, the activity of glyphosate decreased steadily.

It seems that the leaf nyctinasty in velvetleaf makes it irrational to apply nicosulfuron with the AD/S nozzle before sunrise, given the lowest air temperature and the highest relative humidity. However, the current study results show that nicosulfuron application before sunrise is rational if the AD/D and AD/T nozzles are used. Already, we have observed a similar result with trifloxysulfuron against velvetleaf (Aliverdi, Ahmadvand, 2021). As mentioned above, the difference between the performance of the AD/D and AD/T nozzles should be related to the difference in the size of spray droplets produced by them. However, the role of the increased spray pattern of the AD/T nozzle as compared to the AD/D nozzle should not be ignored. The AD/T nozzle creates one vertical spray and two non-vertical sprays (one with 40° forward and another with 40° backward to the direction of nozzle trajectory), while the AD/D nozzle does not create vertical spray. Aliverdi and Karami (2020) have reported that the performance of a triplet flat fan nozzle was better that of AD/D nozzle.

Conclusion

In conclusion, the best time of day for applying nicosulfuron to control johnsongrass and velvetleaf was in the early morning. However, given velvetleaf undergo leaf nyctinasty depending on daylight, the early morning applications only when it is rational that the AD/D nozzle or preferably the AD/T nozzle were used. The performance of the AD/S, AD/D, and AD/T nozzles depends on the application time of nicosulfuron of day. So, when nicosulfuron was used at 5:00 to 11:00, a performance of the AD/T > AD/D > AD/S nozzles could be observed. It seems that high air temperature and low relative humidity cause reduced activity of nicosulfuron. In those weather conditions, a method causing the spray droplets to become smaller (for example, increasing the number of flat fans in a nozzle and decreasing the nozzle flow rate) will cause the spray droplets to evaporate faster, resulting in less activity of nicosulfuron.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

AkA – analysis and interpretation of data and writing a manuscript;
AbA – acquisition of data;
JCF – writing, revision, and approve the final manuscript.

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