Response of sunflower to drift rates of synthetic auxin herbicides used in rice fields (#88643)

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Response of sunflower to drift rates of synthetic auxin herbicides used in rice fields

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The number of herbicide-resistant weed biotypes is increasing in rice fields which has led to the agrichemical industry launching new herbicides, especially new site of actions. Excessive or inappropriate use of these herbicides has resulted in unintended and undesired results near the application fields, such as herbicide drift. This study was conducted to determine the impact of drift (i.e. sub-lethal rates) of quinclorac and florpyrauxifen-benzyl+penoxsulam (FBP) on the yield and yield components (plant height, head diameter, and one-thousand seed weight) of two sunflower varieties. In a climate room experiment, quinclorac and FBP were applied to 2-4 true leaf stages at rates ranging from 2.93 to 93.75 and from 0.51 to 16.25 g ai ha^{-1}, respectively. Visual injury of sunflower varieties increased as rates of quinclorac and FBP increased and reached 37-41% at 93.75 g ai ha^{-1} quinclorac 28 days after treatment (DAT), while the FBP rates that were higher than 2.03 g ai ha^{-1} killed all seedlings of the Bosfora variety. Nonlinear regression analyses indicated that the Bosfora variety was more sensitive to quinclorac and FBP than the Tunca variety. In a field experiment, sunflower varieties were treated with 1/8, 1/16 and 1/32 of the X rate of quinclorac (135 g ai ha^{-1}) and FBP (65 g ai ha^{-1}) when they were at the 8-10 true leaf stage. Quinclorac drift rates resulted in 52-61% sunflower injury at harvest, while crop injury caused by FBP ranged from 85 to 100%. Sunflower yield decreased as quinclorac rates increased, and quinclorac applied at 11.72, 23.44, 46.88 g ai ha^{-1} reduced sunflower yield by 17-25, 46-58, and 82-88%, respectively. The lowest rate of FBP resulted in a 74-80% yield reduction while the higher rates led to a 100% sunflower yield reduction. Correlation analysis revealed that there were strong relationships between injury rates and yields or yield components.

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Abstract

The number of herbicide-resistant weed biotypes is increasing in rice fields which has led to the agrichemical industry launching new herbicides, especially new site of actions. Excessive or inappropriate use of these herbicides has resulted in unintended and undesired results near the application fields, such as herbicide drift. This study was conducted to determine the impact of drift (i.e. sub-lethal rates) of quinclorac and florpyrauxifen-benzyl+penoxsulam (FBP) on the yield and yield components (plant height, head diameter, and one-thousand seed weight) of two sunflower varieties. In a climate room experiment, quinclorac and FBP were applied to 2-4 true leaf stages at rates ranging from 2.93 to 93.75 and from 0.51 to 16.25 g ai ha^{-1}, respectively. Visual injury of sunflower varieties increased as rates of quinclorac and FBP increased and reached 37-41% at 93.75 g ai ha^{-1} quinclorac 28 days after treatment (DAT), while the FBP rates that were higher than 2.03 g ai ha^{-1} killed all seedlings of the Bosfora variety. Nonlinear regression analyses indicated that the Bosfora variety was more sensitive to quinclorac and FBP than the Tunca variety. In a field experiment, sunflower varieties were treated with 1/8, 1/16 and 1/32 of the X rate of quinclorac (135 g ai ha^{-1}) and FBP (65 g ai ha^{-1}) when they were at the 8-10 true leaf stage. Quinclorac drift rates resulted in 52-61% sunflower injury at harvest, while crop injury caused by FBP ranged from 85 to 100%. Sunflower yield decreased as quinclorac rates increased, and quinclorac applied at 11.72, 23.44, 46.88 g ai ha^{-1} reduced sunflower yield by 17-25, 46-58, and 82-88%, respectively. The lowest rate of FBP resulted in a 74-80% yield reduction while the higher rates led to a 100% sunflower yield reduction. Correlation analysis revealed that there were strong relationships between injury rates and yields or yield components.

Key words: Quinclorac, florpyrauxifen-benzyl+penoxsulam, sunflower, crop injury, drift

Introduction

Thrace, located on the western side of Turkey, is a prominent growing region and produces large quantities of wheat, canola, sunflower, and rice as well as grapes for wine due to its fertile soils, water availability, and ideal climatic conditions. This region alone provided 44.5% of the domestic rice and 41.1% of sunflower production in 2021 (TUIK, 2022); furthermore, the agricultural productivity of this region has created a rich agricultural industry surrounding processing these crops, including oil and feed factories, mills, and food companies. It should be noted that although this region produces a majority of the sunflower and rice that Turkey consumes, one-third of sunflower and one-fifth of rice consumed in Turkish markets are imported from abroad (TUIK, 2022). Moreover, Turkey ranked first among countries that import sunflower in 2021 (OEC, 2023). Under pressure to produce more, growers from this region control pests, diseases and weeds via chemical control and have reduced numbers of fields in fallow; therefore, a significant portion of the sunflower fields are adjacent to the rice paddies in the region.

Chemical weed control has several advantages for rice farmers in the Thrace region of Turkey. Over reliance on only a few modes of action has led to the number of weed accessions that have developed resistance to herbicides to increased in the paddy fields in the region (Altop et al., 2014; Haghnama and Mennan, 2020; Kacan et al., 2020). Farmers were largely unaware of resistance evolution, which accelerated the loss of the recommended rates of herbicides important ALS and ACC inhibitors (Serim et al., 2020). To address this problem, some pesticide producing companies have launched alternatives to these common herbicides, including synthetic auxins, in 2019 (PPPD, 2022). Although these products were registered for use in post-emergence weed control, many growers have been using them twice in a season; first as a conventional treatment when the weeds were at the 2-4 true leaf stages, and the second as spot applications when the weeds reached panicle initiation. Spot spraying is often done using a knapsack mist blower. This practice of spot spraying late in the season has increased the off-target movement (OTM) risk of synthetic auxin herbicides from rice fields to sunflower fields of the Thrace Region. Previous research indicated that the severity of the drift caused by herbicide may change depending on the herbicide molecule, rate of the herbicide, application parameters, weather conditions and non-target crop species (Cederlund, 2017). Sunflower is considered one of the most sensitive crops to herbicide residues and drift, especially synthetic auxins, ALS and EPSP inhibitors (Greenshields and Putt, 1958; Lanini and Carrithers, 2000; Serim and Maden, 2014; Serim, 2022). Wall (1996) estimated that 2.4-D can result in upwards of 93-100% yield reduction when applied at 151.2 g ai ha^{-1} in sunflower. Additionally, herbicide drift has threatened the sustainable use of herbicides in agricultural fields. New studies have shown that sub-lethal rates of herbicides may reduce the sensitivity of weeds against herbicides (Vieira et al., 2020).

Quinclorac and florpyrauxifen-benzyl are new herbicide active ingredients registered to control weeds in paddy fields of Turkey as of three years ago (PPPD, 2022). Quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) is a Group 4 herbicide that is thought to have two modes of action; 1) it seems to prevent cell wall biosynthesis and has been shown to increase ethylene and cyanide production in grassy weeds while 2) it seems to mimic native auxin when applied to broadleaves weeds (HH, 2014). This herbicide can cause significant injury on sensitive crops that grow adjacent to fields where it is applied, especially broad leaf crops, including tomato, pepper, cotton, and tree species (Snipes et al., 1992; Lovelace et al., 2007; Adams et al., 2017; Kaya et al., 2023). Globally, some legislative tools have been put into practice to reduce the risk of crop injury and protect susceptible crop species grown near quinclorac application fields. For instance, in Canada, The Health Canada Pest Management Regulatory Agency restricted quinclorac application adding requirements such as droplet size, boom height, and the weight of buffer zone between the application point and sensitive crops (RVD2016-08, 2016).

Florpyrauxifen-benzyl is an auxin-type herbicide (Group 4) belonging to the arylpicolinate chemical family that is used to control weed species in rice fields (HH, 2014). This herbicide's molecule is unique because of its wide herbicidal spectrum (Miller and Norsworthy, 2018a). Previously developed auxin herbicides like quinclorac are used to control narrow-leaf grass weeds, including barnyardgrass (*Echinochloa crus-galli* L. Beauv.), rice flatsedge (*Cyperus iria* L.); smallflower umbrellasedge (*Cyperus difformis* L.); yellow nutsedge (*Cyperus esculentus* L.), whereas florpyrauxifen-benzyl also has the ability to control many broadleaf weed species such as Palmer amaranth (*Amaranthus palmeri* (S.) Wats.), pitted morning glory (*Ipomoea lacunosa* L.), hemp sesbania (*Sesbania hederacea* (P. Mill.) McVaugh), and northern jointvetch (*Aeschynomene virginica* L. Britton, Sterns & Poggenb.). Furthermore, it is often used to kill weed biotypes resistant to ACCs (Group 1) and ALS (Group 2) inhibiting herbicides in paddy fields such as *Echinocloa* spp.

Several dicot crop species are sensitive to florpyrauxifen-benzyl. Miller and Norsworthy, (2018b) note that soybean was the most sensitive to florpyrauxifen-benzyl in tested crops, and moderate injury was observed on the seedlings 14 days after treatment (DAT) at 1/100 of the recommended rate. Schwartz-Lazaro et al. (2017) stated that florpyrauxifen-benzyl applied to soybean resulted in 71 and 31% injury 21 DAT when applied with 1/20 and 1/80 drift rates, respectively. Cotton and sunflower also show severe injury at the 1/10 rate of the herbicide 14 DAT and the herbicidal impact was mitigated by 28 DAT, especially at the 1/100 and 1/500 rates (Miller and Norsworthy, 2018b). Grass crops such as grain sorghum and corn seem to be unaffected by the herbicide (Miller and Norsworthy, 2018b). Because of the sensitivity of some broadleaf crops, florpyrauxifen-benzyl should be used with mitigation measurements to prevent damage on broadleaf crops. Therefore, recommendations should include a buffer zone and/or the use of drift reduction nozzles to protect non-target plants in some countries (Arena et al., 2018).

Although some studies have reported the impact of the sub-lethal doses of the previous types of synthetic auxin herbicides on sunflower, the efficacy of the new generation herbicide synthetic auxin herbicide like florpyrauxifen-benzyl (+ penoxsulam), has not yet been studied. Off target effects of synthetic auxins is not unique to Turkey and has the potential to be problematic in many countries where rice and sunflower fields are in close proximity such as Italy, Greece, Russia, Argentina, Spain, Ukraine, and Bulgaria. The aim of this study was to determine the impact of sub-lethal rates of florpyrauxifen-benzyl + penoxsulam and quinclorac used in rice fields on the growth and yield of sunflower varieties.

Material and Methods

Climate room experiments

A bioassay study was conducted in a climate chamber adjusted to 25±1°C/20±1°C with a 12/12 h day/night photoperiod to determine the sensitivity level of two commercial sunflower varieties, Bosfora and Tunca, to sub-lethal rates of florpyrauxifen-benzyl + penoxsulam and quinclorac caused by aerial drift and contaminated irrigation water. The climate chamber was set light to HPI-T Plus Metal Halide lamps (400 W). Three to four sunflower seeds were sown in plastic pots

(7x7x8.5 cm) filled with white peat bedding substrate (TS 1, Klassman-Deilmann GmbH). Following emergence, the seedlings were reduced up to two in each pot. The pots were arranged in a randomized complete block design with four replications.

In the experiment, the seedlings were treated with seven herbicide rates (0, 2.93, 5.86, 11.72, 23.44, 46.88, and 93.75 g ai ha^{-1} for Quinclorac and 0, 0.51, 1.02, 2.03, 4.06, 8.13, and 16.25 g ai ha^{-1} for florpyrauxifen-benzyl+penoxsulam) at the 2-4 true leaf stage. Quinclorac and florpyrauxifen-benzyl+penoxsulam label rates were 375 and 65 g ai ha^{-1} respectively (PPPD, 2022). Herbicides were applied using a motorized backpack sprayer equipped with flat-fan nozzles (Teejet XR11002) and calibrated to deliver 195 L ha^{-1}. The seedlings were irrigated using tap water as needed. The seedlings were cut from ground level to determine above ground dry weight and stored in a drying oven at 60°C for 48 h, 28 DAT.

The data from the dose–response study were evaluated using a nonlinear regression model in R statistical software (R Core Team, 2023). The DRC package was used to calculate the dose–response curve and parameters with a four parametric log-logistic model (Formula 1).

$$Y = c + \frac{d - c}{1 + \exp\left(b(\log(x) - GR50)\right)} \qquad (1)$$

where y represents seedling dry matter at herbicide treatment rate x; b, c, d, and GR_{50} represent slope, lower limit, upper limit, and herbicide rate that reduced seedling dry matter by 50%, respectively.

Field experiments

Two field experiments were conducted at Bilecik Seyh Edebali University Asagikoy Agricultural Application and Research Centre (AAARC) in 2021 and 2022 to determine the response of sunflower cultivars to sub-lethal rates of florpyrauxifen-benzyl and quinclorac. The soil texture at AARC was silty clay with 2.4% om, pH 8.13. Field studies were arranged within a randomized complete block design with four replications. Conventional sunflower varieties, Bosfora and Tunca, were sown to 70 cm spacing in plots consisting of four parallel rows, and di-ammonium phosphate was applied during the sowing at 80 kg ha^{-1} using a combine type seed-driller on April 11, 2021, and May 02, 2022. In this study, the temperature and rainfall in 2021 and 2022 were close to long-term averages (12.1 and 12.7°C and 449.2 and 478.9 mm, respectively).

Florochloridone was applied prior to emergence at a 700 g ai ha^{-1} rate in 2021, while pendimethalin was used two days after sowing at a 1.350 g ai ha^{-1} rate to control weeds in 2022. Plot sizes were 2.8 m wide and 10 m long. Two crop rows between the herbicide-applied plots were left as allays to avoid contamination between the plots.

Quinclorac and florpyrauxifen-benzyl+penoxsulam rates were 11.72, 23.44, 46.88 g ai ha^{-1} and 2.03, 4.06, and 8.13 g ai ha^{-1} respectively, which were equivalent to 3.125, 6.250, and 12.5% of the recommended use rates (PPPD, 2022). The aforementioned rates of herbicides were applied when the sunflower reached 8-10 true leaves. Sunflower injury caused by these herbicide rates was recorded 7, 14, and 28 d after treatment (DAT) based on a scale of 0-100%, where 0% indicated no impact of herbicides, while 100% represented complete plant death and then harvested 28DAT. At harvest, five plants from the middle two rows of each plot were randomly selected and harvested by hand on September 05, 2021, and October 04, 2022. The heights of the selected plants, sunflower head diameter (SHD), 1000-seed weight (OTSW), and yield were measured (Serim & Maden, 2014).

All data are presented as the percentage of the non-treated control and were analyzed with ANOVA for each herbicide and variety, and mean separation was performed with Fisher's protected LSD test at the 5% level of probability. The agricolae package (de Mendiburu and Yaseen, 2020) was used in the R statistical software program (R Core Team, 2023). The Pearson correlation test was used to find a relationship between the herbicide injuries measured at 4 different times and the yield (and yield components).

Results and Discussion

Climate Room Studies

H. annuus var. Tunca exposed to low rates of florpyrauxifen-benzyl+penoxsulam were severely injured (Figure 1a). However; the lowest rate of herbicide unexpectedly increased shoot length, which may be caused by the hormetic impact of auxinic herbicides, similar to that previously reported by Mudge et al. (2021). Overall, shoot lengths decreased as the rates increased. The impact of the higher four rates of herbicide was the most destructive, and the growing points of var. Bosfora were completely killed by these rates 28 DAT. More than half of the leaf area of seedlings exposed to these rates became necrotic. The response of var. Bosfora to FBP were similar to var. Tunca, except at rates higher than 1.02 g ai ha^{-1} where it appeared to be more injured (Figure 1a and 1b).

Injury from quinclorac increased over time, with a slight and gradual increase in sunflower injury with rate. By 28 DAT, the highest sunflower injury was caused by the highest rate of quinclorac (Figure 1). The response of these sunflower varieties to lower rates of quinclorac was very similar, however var. Bosfora was slightly more sensitive to quinclorac than var. Tunca at higher rates. As opposed to FBP, sunflower plants treated with quinclorac still had alive growing points, and necrotic areas on the seedling leaves were relatively limited even at the highest rates. At the lowest rates, FBP resulted in no damage on these varieties, while at the lowest dose of quinclorac growth reduction was still observed.

The quantitative response of var. Tunca and var. Bosfora to FBP and quinclorac was evaluated via a dose–response assay using a log-logistic model. The GR_{50} values of FBP for Tunca and Bosfora were 1.07 and 0.75 g ai ha^{-1}, respectively (Table 1). These values were nearly 2-2.9% of the recommended rate of FBP (65 g ai ha^{-1}). The GR_{50} values of quinclorac for sunflower varieties were 14.16 and 7.56 g ai ha^{-1}. The values were 2-3.8% of the recommended rate of quinclorac (375 g ai ha^{-1}). Similar to the visual herbicidal impact of FBP and quinclorac, the results show that FBP was slightly more injurious than quinclorac.

Field Experiment

Sunflower crops exposed to FBP and quinclorac responded immediately after treatment, especially the leaves. FBP resulted in typical auxin symptoms, such as parallel veins, cupping, twisting, chlorosis, and distortion (Figure 2). Quinclorac also caused these symptoms, except distortion (Figure 3). The severity of symptoms was higher in var. Bosfora than for var. Tunca and increased as the rates increased. Stunting became apparent 28 DAT for both varieties. The highest rate of FBP prevented the establishment of sunflower heads in both varieties (Figure 4).

Quinclorac and FBP injury was limited at 7 DAT, and no difference was found between var. Tunca and var. Bosfora (Figures 5, 6A and 6B). The response of sunflower varieties to FBP increased as the rates rose and reached 75-77.5% at 8.13 g ai ha^{-1} 7 DAT (Figure 6A and 6B). Quinclorac injury on var. Bosfora (13.75-33.75%) and var. Tunca (17.5-30%) were lower than those of FBP. At 14 DAT, the response of the varieties to the herbicides was generally similar to that at 7 DAT. Sunflower injury due to FBP increased with the increase in herbicide rates from 2.03 to 8.13 g ai ha^{-1} 28 DAT. var. Bosfora exposure to quinclorac at 11.72, 23.44, and 46.88 g ai ha^{-1} resulted in 15, 22.5, and 38.75% injury, respectively, while var. Tunca was less sensitive to these rates.

FBP injury worse by 28 DAT, and the growing points of plants were completely killed at the highest rate, while the lowest FBP rate resulted in sunflower injury of 76.25-88.75%. Differences between sunflower varieties became more apparent at 28 DAT. Although the phytotoxicity of quinclorac increased at 28 DAT, crop injury caused by the herbicide was nearly half that of FBP.

Visible injury rates reached the greatest level at harvest. Sunflower injury at 2.03 g ai ha^{-1} FBP was higher than >90% for var. Bosfora and >85% for var. Tunca. The highest FBP rate led to complete death of both sunflower varieties. The injury increased in severity as the quinclorac rate increased in both varieties. The injury on vars. Bosfora and Tunca ranged from 42.5-57.5% and from 36.25-48.75%, respectively. The severity of injury due to quinclorac was limited to 7 DAT because injury assessment was only employed on the leaves, while this influence was more apparent in evaluations of other crop parameters, including plant height, stem structure, size of flower bud and head, were included in the evaluations. Compared to quinclorac, FBP was more phytotoxic to both varieties, and this destructive impact was observed even from the first assessments 7 DAT.

The heights of the sunflower varieties constantly declined as the FBP and quinclorac rates increased. FBP rates displayed a significant decrease in the plant height of the sunflower varieties. The highest rate of FBP resulted in a 32-44% reduction in plant height, while the lowest decline in plant height occurred at 8-9% (Figure 7a). Sunflower height reduction from quinclorac at 46 g ai ha^{-1} was 25-32%, whereas at 11.72 g ai ha^{-1}, it was 13-14%. The increase in FBP and quinclorac rates caused SHD decline regardless of the variety. The greatest percentage of decline resulting from FBP was recorded at 6.25 g ai ha^{-1} with 76-77%. No flower heads were observed in the plots treated with 6.25 g ai ha^{-1} FBP, whereas this rate prevented sunflower flowering (Figure 3). SHD reduction in var. Bosfora and var. Tunca from quinclorac ranged from 19-57% and 9-51%, respectively (Figure 7b). A slight decrease was observed in TSW compared to plant height and SHD, but the decrease even at the highest level of herbicide was no more than 21% (Figure 7c). Sunflowers exposed to higher FBP rates, 6.25 and 12.5 6.25 g ai ha^{-1}, could not produce mature seeds. The results showed that TSW was a less susceptible yield component to FBP drift rates than the others.

Associated with other yield components, significant sunflower yield loss was determined even at lower rates of quinclorac and FBP (Figure 7d). The highest yield reduction was observed for sunflower varieties treated with FBP at 6.25 and 15.5 g ai ha^{-1} at 100%. The lowest FBP rate reduced var. Bosfora and var. Tunca yield 79.8 and 74.3%, respectively. Yield reduction of var. Bosfora from quinclorac rates were 45.1-87.9%, while yield loss caused these rates to range from 16.3-82.3%. Yield data clearly showed that var. Bosfora was more sensitive to FBP and quinclorac rates than var. Tunca.

Very high Pearson correlation coefficients were found between Quinclorac Injury 7 or 14 DAT and plant height (Table 2). The negative relations between Quinclorac Injury 7 or 14 DAT and SHD, TSW and yield were also high, but their significance was slightly below the relations between Quinclorac Injury 7 or 14 DAT and plant height. At 28 DAT, plants treated with quinclorac began to recover from treatment and the yield and yield component was higher compared to previous evaluatıon times (i.e. 7 and 14 DAT). Quinclorac injury at 28 DAT had a less representative ability to the adverse impact of quinclorac on yield and yield component compared to previous evaluation times, 7 and 14 DAT. Correlation analysis showed that a slightly higher correlation was found between plant height (PH) and Injury at 7 or 14 DAT than in Injury at 28 DAT and at harvest. Similar trends were observed between SHD or TSW and injury at 7, 14, and 28 DAT and harvest. Although there was a strong positive relationship between PH and yield, the importance of the relationship was greater than that of other relationships.

Discussion

Synthetic auxin herbicides were the first synthetically derived, selective, chemicals for weed control. Although their use has been continued for more than 70 years, they are also among the most used herbicide groups. The use of these relics are only increasing as the number of herbicide-resistant biotypes for other modes of action (MoA) increases. As a consequence, many Auxins have been implemented in rice, but using these herbicides in rice fields may increase drift risk on sensitive crops such as cotton, tomato and sunflower, which are grown near or adjacent to rice paddies.

The impact of auxin herbicides on sunflowers has been reported in many studies. Schroeder et al. (1979) stated that 2,4-D and dicamba resulted in tremendous injury to sunflowers. The deleterious impact of these herbicides was higher when exposed to the pre-flowering stage rather than the early growing stage (such as the 2-4 true leaf). We see similar findings in our work for the auxinics quinclorac and FBP applied at the 8-10 leaf stage.

Quinclorac is well-known to cause drift injuries in sensitive crops grown adjacent to spraying areas. Snipes et al. (1992) reported that 17 ai g ha^{-1} or higher rates of quinclorac may injure cotton when applied at the cotyledon stage, and cotton injury increased with increasing herbicide rate, especially during late-stage applications, such as at the pin-head square stage. Overall, the cotton injury rate reached 59% at 140 ai g ha^{-1} in their study, and sunflower injury caused by quinclorac at 46.88 ai g ha^{-1} was 52-61.25% in our study.
Comparing these results to those of Snipes et al. (1992), sunflower can be classified as a more sensitive crop than cotton. A study conducted by Lovelace et al. (2007) revealed that tomato was also among quinclorac-sensitive crops, and crop injury caused by quinclorac applied at 42 ai g ha^{-1} was 45% at 49 DAT. In our study, the third evaluation was done at 55 DAT, and crop injuries were 48.75-57.5% when herbicide was applied at 46.88 ai g ha^{-1}. These data are consistent with the work of Lovelace et al. (2007). Moreover, sunflower has been shown to be so sensitive to sub-lethal rates of quinclorac, it was used as a bioassay plant to detect herbicide residues in the soil (Lym, 2016).

Florpyrauxifen-benzyl is a relatively new herbicide on the market; therefore, few drift studies are available in the literature. Miller and Norsworthy (2018b) indicated that 3 ai g ha^{-1} florpyrauxifen-benzyl applied to sunflowers at the three true-leaf stage resulted in 69% injury, 66% plant height reduction, and 30% biomass reduction 28 DAT in greenhouse conditions. In our study, FBP containing 2.03 ai g ha^{-1} florpyrauxifen-benzyl+penoxsulam caused 76 and 89% injury 28 DAT on var. Tunca and var. Bosfora, respectively.

Crop varieties can have various genetic backgrounds depending on the breeding aim; therefore, it is not surprising that they respond differently to abiotic stressors, including drought stress, heat stress, and herbicides. Balkan Nalçaiyi (2018) found var. Tunca and var. Bosfora had different responses to drought stress; the first was classified as sensitive to drought, while the latter was moderately tolerant. Although sources of abiotic stress are quite diverse, often plants use similar defense mechanisms to protect themselves from the adverse impacts of these stressors. Chandi et al. (2013) indicated that there is a positive relationship between herbicide resistance and drought stress in palmer amaranth biotypes. When we considered these studies, it was clear that var. Tunca was more tolerant to abiotic stress conditions, such as synthetic auxin herbicides, than var. Bosfora. Using herbicide-tolerant crop varieties is a cost-effective and reliable solution to prevent the injurious impact of herbicide drift on sensitive crops. This phenomena has been shown in other studies of Zangoueinejad et al. (2021), France et al. (2022) and Warmund et al. (2022), who show differences between the tolerance levels of soybean, melon, and tomato varieties to synthetic auxin herbicides dicamba and 2.4-D and 2.4-D or Dicamba, respectively.

The correlation analysis performed in this research can be a powerful tool to estimate the injurious impact caused by drift rates of synthetic auxin herbicides on yield and yield components long before harvest. In our study, strong relationships between injury rates and yields (or yield components) were similar to those found in previous studies (Lovelace et al., 2007; Marple, Al-Khatib and Peterson, 2008; Daramola et al., 2023). The ability to model injury rates and yield loss resulting from herbicides provide an opportunity for farmers to decide whether to stop or continue current agricultural practices. If herbicide damage reduced farmer's income below the total expenses, farmers may wish to change their management in order to remain profitable; therefore, correlation analysis between herbicides and yield can be used as a decision-support tool for farmers.

Conclusions

Each new herbicide introduced into the market is a wondrous new tool for farmers, which often causes them to launch into intensive use without proper caution. These new synthetic auxin herbicides for rice exemplify this due to their destructive impact on susceptible crops such as sunflowers. Although MOAs can be the same for two herbicides, the crop response to them is often not (Eganet al., 2014). In this study, two synthetic auxin herbicides applied to sunflower varieties resulted in different injury symptoms and yield losses from different varieties of sunflowers. Therefore, rice growers should be attentive to weather conditions, application parameters, herbicides, herbicide properties, and the safety measurements given by pesticide advisors to prevent drift risk on sunflowers, especially when UAVs are used for spraying. Moreover, sunflower producers should be careful about the location of sunflower fields prior to sowing and choose more tolerant sunflower varieties to synthetic auxin herbicides instead of sensitive ones.

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Table 1 (on next page)

Table 1. Nonlinear regression parameters of florpyrauxifen-benzyl+penoxsulam and quinclorac [a]

[a]: Abbreviations: FBP, florpyrauxifen-benzyl + penoxsulam; b: slope of the curve at GR_{50}; c: lower limit; d: upper limit; GR_{50}: herbicide rate that reduced seedling dry matter by 50%; Comp: comparison rate ($GR_{50bosfora}$/$GR_{50tunca}$); Sig: significance ($P<0.05$).

Herbicide	$b_{bosfora}$	b_{tunca}	c	d	$GR_{50bosfora}$	$GR_{50tunca}$	Comp	Sig.
Quinclorac	3.22	1.66	0.39	3.31	0.75	1.07	0.70	0.035
FBP	1.91	4.34	1.57	3.24	7.56	14.16	0.53	0.007

Table 2(on next page)

Table 2. Pearson correlation coefficients among the evaluation times after herbicide application and herbicide dose, yield, yield components, plant height, sunflower head diameter, and one thousand seed weight.

PH; plant height; SHD: sunflower head diameter; TSW: one thousand seed weight; I7DAT: injury at 7 DAT; I14DAT: injury at 14 DAT; I28DAT: injury at 28 DAT; IHarvest: injury at harvest **: $P<0.05$; ***: $P<0.01$

	Dose	PH	SHD	TSW	Yield	I7DAT	I14DAT	I28DAT	IHarvest
Dose	1								
PH	-0,88***	1							
SHD	-0,95***	0,87***	1						
TSW	-0,92***	0,75**	0,95***	1					
Yield	-0,90***	0,74**	0,93***	0,95***	1				
I7DAT	0,94***	-0,94***	-0,88***	-0,85***	-0,87***	1			
I14DAT	0,95***	-0,93***	-0,91***	-0,87***	-0,88***	0,99***	1		
I28DAT	0,82**	-0,87***	-0,85***	-0,82**	-0,87***	0,93***	0,93***	1	
IHarvest	0,82**	-0,86***	-0,86***	-0,83**	-0,87***	0,92***	0,93***	1	1

Figure 1

Figure 1. Response of Tunca (A and C) and Bosfora (B and D) varieties to florpyrauxifen-benzyl+penoxsulam (A and B) and quinclorac (C and D) rates in the climate room.

Figure 2

Figure 2. Dose–response curves of florpyrauxifen-benzyl + penoxsulam (left) and quinclorac (right) applied to var. Bosfora and var. Tuna

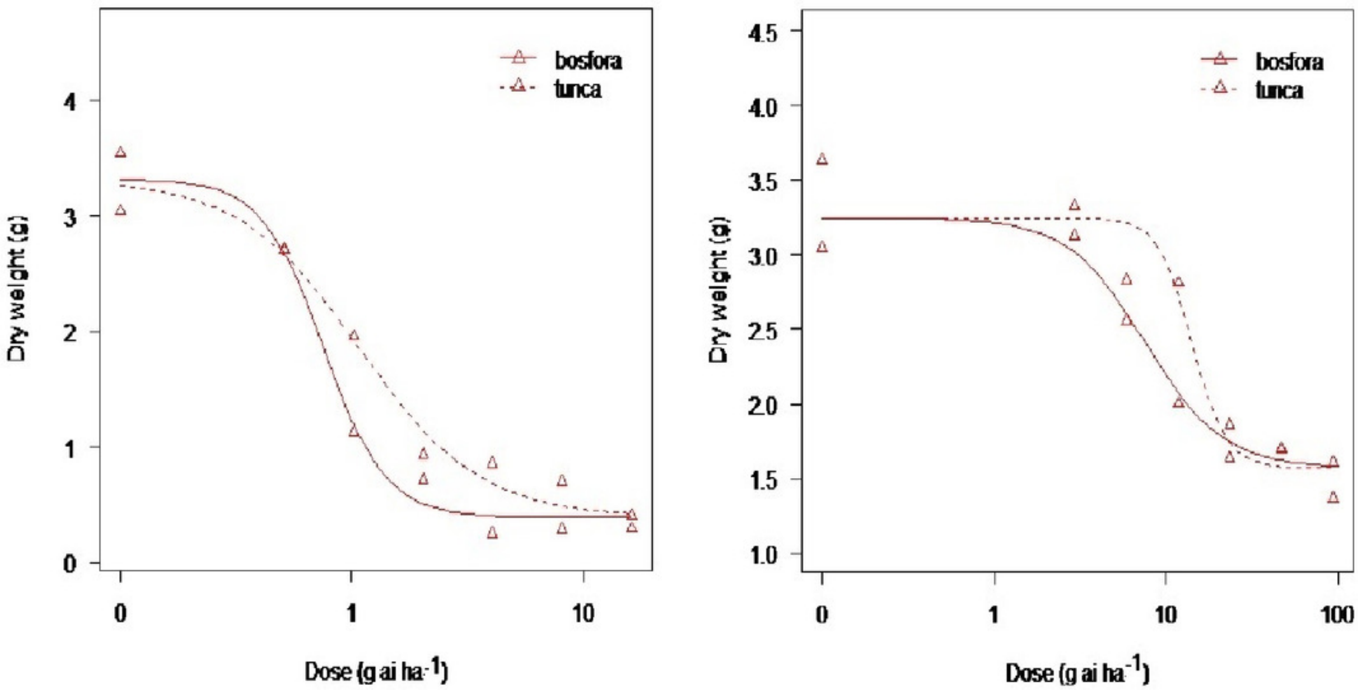

Figure 3

Figure 3. Impact of FBP on sunflower (var. Bosfora) 28 DAT in 2022 (left: lowest drift rate; middle: moderate drift rate; right: highest drift rate)

Figure 4

Figure 4. Impact of quinchlorac on sunflower (var. Bosfora) 28 DAT in 2022 (left: lowest drift rate; middle: moderate drift rate; right: highest drift rate)

Figure 5

Figure 5. Efficacy of drift rates of florpyrauxifen-benzyl+penoxsulam (B and D) and quinclorac (A and C) on heads of Tunca (A and B) and Bosfora (C and D) varieties (X: recommended rate).

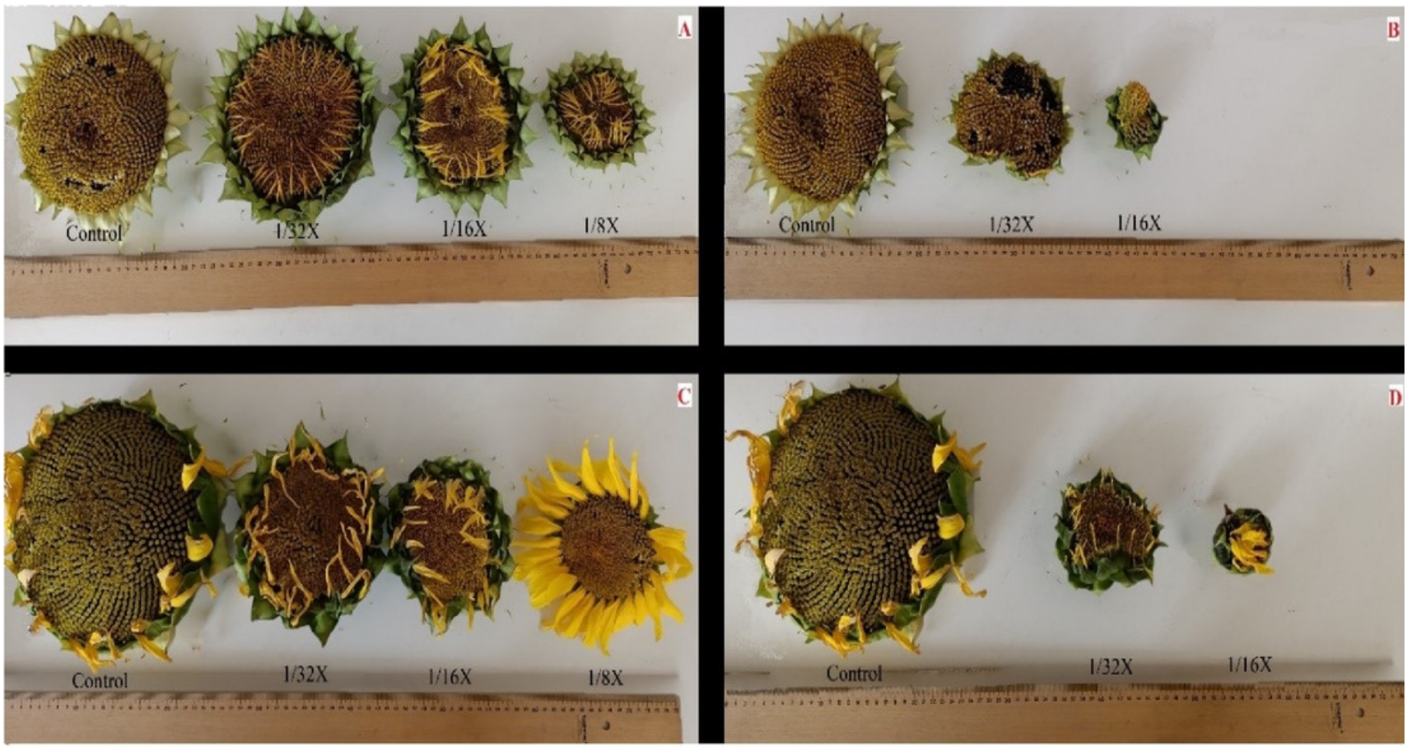

Figure 6

Figure 6. Florpyrauxifen-benzyl+penoxsulam (FBP) and quinclorac (Q) injury on the sunflower var. Bosfora (A) and var. Tunca (B) 7, 14, 28 DAT, and harvest (%)

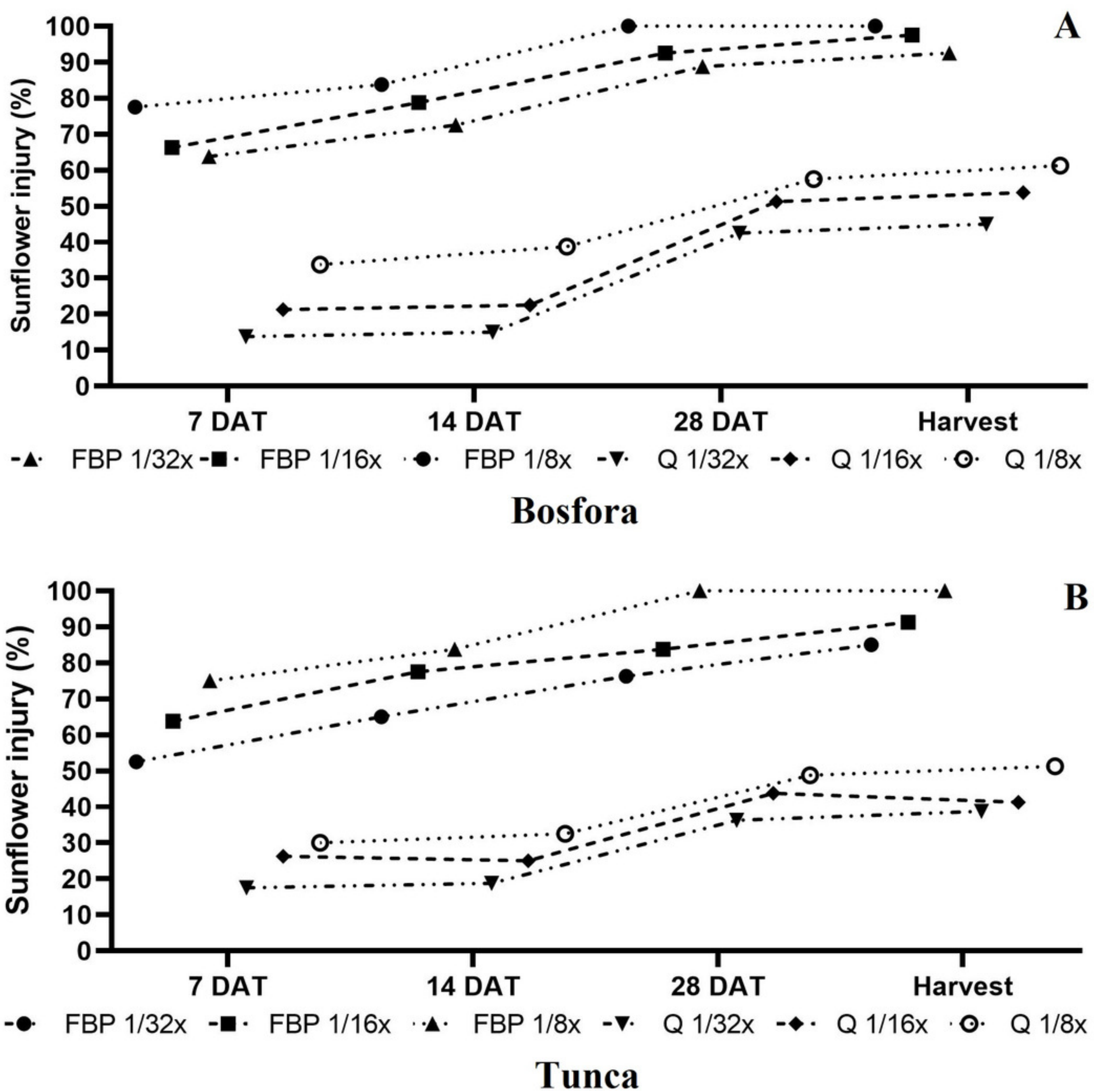

Figure 7

Figure 7. Yield and yield components of sunflower varieties in response to FBP and quinclorac (a: Plant height; b: Sunflower head diameter (cm); c: One thousand seed weight (g); Yield (kg ha^{-1}))