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# Synergism of the commercial mixture of atrazine and mesotrione for post-emergence control of *Conyza* spp.

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## ABSTRACT

The atrazine + mesotrione mixture exhibits variable synergism depending on dose and species. This study evaluated the efficacy and synergistic potential of this commercial mixture in controlling hairy fleabane. A greenhouse dose-response experiment was conducted using a completely randomized design with fourteen treatments and four replications. Atrazine was applied at doses of 62.5-2000 g a.i. $ha^{-1}$ alone and in a commercial mixture with mesotrione, in addition to mesotrione applied alone (100 g a.i. $ha^{-1}$) and an untreated control. Control levels and biomass reduction were assessed up to 35 days after treatment, along with shoot fresh and dry weights. Subsequently, an analysis of variance was performed ($P < 0.05$), and three-parameter log-logistic regressions were fitted. The effect of the commercial mixture was calculated using Colby's method. Results showed atrazine alone required the highest dose for satisfactory control (>80%). Conversely, the commercial mixture provided effective control and biomass reduction at 500 g atrazine + 50 g mesotrione $ha^{-1}$. The atrazine C50 values were 897.72 g a.i. $ha^{-1}$ for the application alone and 130.88 g a.i. $ha^{-1}$ for the mixture with mesotrione at 35 DAT. Colby's method confirmed a synergistic interaction between the active ingredients (91% observed vs. 67.9% expected at 35 DAT). Consequently, the atrazine + mesotrione mixture is recommended as an option for post-emergence management of hairy fleabane.

**Keywords:** Formulation, Photosystem II inhibitors, Carotenoid synthesis inhibitors, Herbicide mixture.

# Sinergismo da mistura comercial de atrazina e mesotriona no controle em pós-emergência de *Conyza* spp.

## RESUMO

A mistura de atrazina + mesotriona exibe sinergismo variável dependendo da dose e da espécie. Este estudo avaliou a eficácia e o potencial sinérgico desta mistura comercial para o controle de buva. Um experimento de dose-resposta em casa de vegetação foi conduzido utilizando um delineamento inteiramente casualizado com quatorze tratamentos e quatro repetições. Atrazina foi aplicada nas doses de 62,5-2000 g i.a. $ha^{-1}$ isolada e em formulação com mesotriona, além de mesotriona aplicada isoladamente (100 g i.a. $ha^{-1}$) e uma testemunha sem tratamento. Níveis de controle e redução de biomassa foram avaliados até 35 dias após o tratamento, juntamente com a massa fresca da parte aérea e a massa seca da parte aérea. Posteriormente, foi realizada uma análise de variância ($P < 0,05$) e regressões logísticas foram ajustadas. O efeito da mistura foi calculado utilizando o método de Colby. Os resultados mostraram que a atrazina isolada exigiu a dose mais elevada para um controle satisfatório (>80%). Por outro lado, a mistura proporcionou controle eficaz e redução de biomassa em 500 g de atrazina + 50 g de mesotriona $ha^{-1}$. Os valores de C50 da atrazina foram de 897,72 g i.a. $ha^{-1}$ na aplicação isolada e 130,88 g i.a. $ha^{-1}$ na mistura com mesotriona aos 35 DAT. O método de Colby confirmou interação sinérgica entre os ingredientes ativos (91% observado vs. 67,9% esperado aos 35 DAT). Consequentemente, a mistura atrazina + mesotriona é recomendada como opção para manejo de buva em pós-emergência.

**Palavras-chave**: Formulação, Inibidores do fotossistema II, Inibidores da síntese de carotenoides, Mistura de herbicidas.

## 1. Introduction

The presence of weeds in cultivated areas brings numerous losses to production systems. Characterized by their high adaptability and competitiveness, weeds cause yield losses, increase production costs, and impair final product quality if not controlled at the appropriate time (Rüdell et al., 2021). Among the main weed species is hairy fleabane (*Conyza* spp.), which is characterized by its high seed production and efficient wind dispersal (Amaral et al., 2020). It is a highly competitive weed, and if not managed, it can cause losses of up to 70% in soybean grain yield (Lorenzetti et al., 2025). In addition to competition, hairy fleabane is known to cause other interferences, such as hosting important insect pest species of the soybean crop (Dalazen et al., 2016).

Another characteristic of hairy fleabane is the occurrence of populations resistant to glyphosate and other herbicides (HEAP, 2025). Since the first record of resistance to glyphosate, reported in 2005 in the state of Rio Grande do Sul, the dispersal of glyphosate-resistant hairy fleabane biotypes has increased considerably in all regions of Brazil (Mendes et al., 2021). The repeated and exclusive use of glyphosate, especially following the widespread adoption of crops tolerant to this herbicide, has contributed to the intensification of this resistance scenario. Currently, more than 16 million hectares in Brazil are infested with glyphosate-resistant hairy fleabane (Lucio et al., 2019). In addition to glyphosate resistance, cases of multiple resistance have been identified, including to herbicides such as chlorimuron-ethyl (an acetolactate synthase (ALS) inhibitor) and 2,4-D (an auxin mimic), among others (HEAP, 2025).

Among the management strategies for glyphosate-resistant weeds, rotating herbicides with different mechanisms of action is recommended (Neve et al., 2017). This measure interrupts the multiplication cycles of plants resistant to a specific herbicide. For hairy fleabane management, the herbicide atrazine is recommended for applications in the maize crop and for early management during the fall/winter period. Atrazine acts by binding to the quinone B (QB) binding site on the D1 protein of photosystem II (PSII). Consequently, accumulated electrons reduce molecular oxygen, generating reactive oxygen species (ROS) that damage cell membranes. Due to ROS-induced damage, tissue necrosis is common, especially in mature leaves, as the herbicide is translocated through the xylem (Giraldeli et al., 2024). For these reasons, its post-emergence use is recommended for plants in early developmental stages, since regrowth is common in larger plants (Sousa et al., 2020).

Exploring synergistic effects is one way to improve the action of atrazine. This can be done by adding carotenoid biosynthesis inhibitors, such as mesotrione, an herbicide that inhibits the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), which plays a key role in the carotenoid biosynthesis pathway. These pigments act as protectors against excess energy in the photosystems. Typical symptoms include bleaching of young tissues following chlorophyll photodegradation after phloem translocation of the herbicide (Oliveira Junior et al., 2021; Giraldeli et al., 2024). Therefore, the absence of carotenoids in plants makes the effect of PSII-inhibiting herbicides even more pronounced, and synergism may occur between these mechanisms of action (Kruse et al., 2001).

The synergistic interaction between herbicides is also often driven by an interplay of physicochemical and physiological traits. These properties, such as pKa and log Kow, can dictate the rates of absorption and translocation within the plant, effectively modulating the concentration of the active molecule at the site of action (Barbieri et al., 2022). For example, the physiological synergy between PSII and HPPD inhibitors has been attributed to altered absorption patterns in certain species, providing a potential basis for the enhanced efficacy of commercial mixtures (Chahal et al., 2019; Fluttert et al., 2022b). Beyond physiological enhancements, another advantage of adding HPPD inhibitors to atrazine is the broadening of the control spectrum over grass weeds (Matte et al., 2018). Furthermore, the commercial mixture reduces the risk of the evolution of resistant biotypes compared to individual applications (Santos et al., 2025).

Although synergism between PSII and carotenoid inhibitors is common, this relationship depends on many factors, such as application stage, formulation, herbicide dose, and weed species (Kruse et al., 2001; Barbieri et al., 2022). The hypotheses of this study are that the combination of atrazine and mesotrione is more effective for post-emergence control of hairy fleabane than atrazine alone, and that this may reflect a synergistic relationship. Given the difficulty in controlling hairy fleabane plants, the objective of this study was to evaluate the efficacy of the commercial mixture of atrazine + mesotrione at different doses for the post-emergence control of hairy fleabane, as well as to investigate the potential synergism between these two active ingredients present in this herbicide.

## 2. Material and Methods

Experimental site and plant material

The experiment was conducted in a greenhouse at the Department of Agronomy of the State University of Londrina (UEL), in the city of Londrina, Paraná (Brazil), between May and August 2022. Hairy fleabane seeds were collected from the UEL University Farm, where glyphosate-resistant populations had previously been reported, and sown in plastic trays containing Carolina Soil® substrate. After 30 days, when the seedlings had two to three leaves, they were transplanted into 1 L pots, with one plant maintained per pot. The substrate used was composed of clay soil (70% clay) and sand in a 1:1 ratio. NPK fertilizer (5-20-20) was added at a rate of 2.5 g $kg^{-1}$ of substrate, as well as dolomitic limestone (ECCE 70%) at a rate of 7.5 g $kg^{-1}$ of substrate. The plants were irrigated daily, maintaining soil moisture near field capacity.

The treatments were arranged in a completely randomized design with fourteen treatments and four replications. Atrazine was applied at doses of 62.5, 125, 250, 500, 1000, and 2000 g a.i $ha^{-1}$. applied alone (Primóleo, 400 g of atrazine $L^{-1}$) and in a commercial mixture with mesotrione (Calaris, 500 g of atrazine $L^{-1}$ + 50 g of mesotrione $L^{-1}$). In addition, mesotrione was applied alone (Callisto, 480 g of mesotrione $L^{-1}$) at a dose of 100 g a.i. $ha^{-1}$, and an untreated control was included. Mineral oil (0.5% v $v^{-1}$) was added to all treatments.

The herbicide treatments were applied when the hairy fleabane plants were at the 8 to 10 leaf stage and approximately 15-20 cm in height. The application was performed using a $CO_2$-pressurized backpack sprayer equipped with a boom containing two XR TeeJet 110.02 flat-fan nozzles, at an operating pressure of 30 psi and a spray volume of 150 L $ha^{-1}$. At the time of application, weather conditions were favorable, with a temperature of 25 °C, relative humidity of approximately 65%, and a wind speed of 2.5 km $h^{-1}$.

Visual assessments of hairy fleabane control were conducted at 7, 14, 21, 28, and 35 DAT. The assessments were always performed by two evaluators, following the visual rating scale proposed by Frans et al. (1986), in which 0 indicates no symptoms, and 100 indicates complete plant death.

At 35 DAT, the aboveground parts of the hairy fleabane plants were manually harvested using pruning shears. Immediately, the samples were weighed to determine the shoot fresh weight (SFW). Subsequently, the samples were placed in paper bags and placed in a forced-air drying oven (60 °C for 72 h). After the drying period, the samples were weighed again to determine the shoot dry weight (SDW). Both fresh and dry weights were expressed in grams per plant.

The data were subjected to tests for homogeneity of variances and normality of residuals. Subsequently, an analysis of variance (ANOVA) was performed ($p<0.05$), and log-logistic three-parameter regressions were fitted using the R Statistical Software (R Core Team, 2026). The dose-response curves were modeled using the DRC package (Ritz et al., 2015) according to the following equation:

$$y=d(1+\exp\{b[\log(x) - \log(e)])$$

Where y is the response variable (percentage of control or growth reduction), x is the herbicide dose (g a.i. $ha^{-1}$), d is the upper limit (fixed at 100%), b is the slope of the curve around the inflection point, and e is the dose required for 50% response (C50 or GR50). From the equation parameters, the C50 and GR50 values were determined. Growth reduction values were converted to a percentage (%) reduction relative to the untreated control. The effect of the commercial mixture (synergism, antagonism, or additivity) was calculated using the method proposed by Colby (1967).

## 3. Results and Discussion

At 7 DAT, hairy fleabane control was already greater in treatments where the atrazine + mesotrione mixture was applied than in treatments where atrazine was applied alone (data not shown). At the highest evaluated dose of the commercial mixture, with an atrazine rate of 2000 g a.i. $ha^{-1}$, control was approximately 20%. In contrast, applying atrazine alone at the same rate resulted in 10% control. At the lowest recommended dose of the atrazine + mesotrione herbicide, corresponding to 500 + 50 g a.i. $ha^{-1}$, control was approximately 14% with the commercial mixture, compared to 10% for atrazine alone. The fitted regressions estimated a C50 value of 2092.74 g a.i. $ha^{-1}$ of atrazine applied alone, versus only 480.75 g a.i. $ha^{-1}$ of atrazine when in a mixture with mesotrione (Table 1).

At 14 DAT, the differences in hairy fleabane control in response to the mesotrione + atrazine mixture and atrazine alone became more evident (Figure 1A). Control of the hairy fleabane plants with the formulated atrazine + mesotrione mixture was approximately 52% and 57% at the rates corresponding to 500 g a.i. $ha^{-1}$ and 1000 g a.i. $ha^{-1}$ of atrazine, respectively. For the standalone atrazine application, control was around 12.5% and 21% at the same rates. The C50 estimated for atrazine alone was 5974.54 g a.i. $ha^{-1}$, compared to only 246.27 g a.i. $ha^{-1}$ when atrazine was in a mixture with mesotrione, which is 24.26-fold lower (Table 1).

**Table 1.** Parameters of the fitted log-logistic regressions for both atrazine and atrazine + mesotrione dose-response curves.

| Evaluation | Herbicide | b (slope) | $C_{50}$ (g a.i. $ha^{-1}$) ± SE | RP | $R^2$ |
|---|---|---|---|---|---|
| 7 DAT | Atrazine | -0.44 | 2092.74 ± 603.00 | --- | 0.77 |
| | Atrazine + mesotrione | -0.47 | 480.75 ± 74.71 | 4.35 | 0.88 |
| 14 DAT | Atrazine | -0.55 | 5974.54 ± 3481.69 | --- | 0.65 |
| | Atrazine + mesotrione | -0.62 | 246.27 ± 38.68 | 24.26 | 0.83 |
| 21 DAT | Atrazine | -0.72 | 2260.78 ± 467.30 | --- | 0.77 |
| | Atrazine + mesotrione | -0.38 | 96.65 ± 26.25 | 23.39 | 0.90 |
| 28 DAT | Atrazine | -0.70 | 1648.00 ± 294.51 | --- | 0.75 |
| | Atrazine + mesotrione | -0.55 | 80.22 ± 17.49 | 20.54 | 0.94 |
| 35 DAT | Atrazine | -1.35 | 897.72 ± 103.73 | --- | 0.75 |
| | Atrazine + mesotrione | -1.02 | 130.88 ± 19.72 | 6.86 | 0.94 |
| Shoot Fresh Weight | Atrazine | -0.48 | 644.51 ± 186.49 | --- | 0.55 |
| | Atrazine + mesotrione | -0.52 | 116.64 ± 37.62 | 5.53 | 0.76 |
| Shoot Dry Weight | Atrazine | -0.08 | 410.41 ± 308.81 | --- | 0.77 |
| | Atrazine + mesotrione | -0.13 | 5.62 ± 10.00 | 73.02 | 0.84 |

b: slope; C50 (GR50): dose for 50% response; RP: relative potency (C50 atrazine/C50 atrazine+mesotrione); $R^2$: coefficient of determination. DAT: days after treatment; SE: standard error. Upper limit fixed at 100% for control.

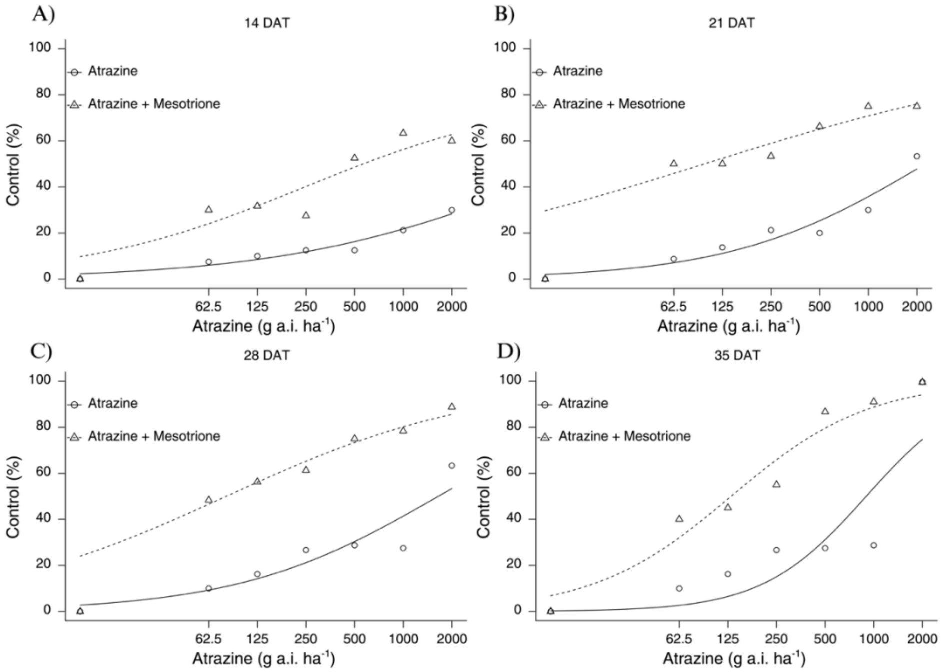


**Figure 1.** Control percentage of *Conyza* spp. in response to atrazine doses applied alone or in a commercial mixture with mesotrione. Evaluations were performed at (A) 14, (B) 21, (C) 28, and (D) 35 days after treatment (DAT). g a.i. $ha^{-1}$: grams of active ingredient per hectare. Symbols represent observed means and lines represent the fitted three-parameter log-logistic model.

At 21 DAT, the results were similar, following the pattern observed in the previous assessment. Hairy fleabane control was significantly greater for all atrazine doses when in a commercial mixture with mesotrione (Figure 1B). At the recommended doses of the atrazine + mesotrione herbicide, equivalent to 500 and 1000 g a.i. $ha^{-1}$ of atrazine, the control levels were 66% and 68%, respectively. In contrast, for the atrazine applied alone at these same doses, the control levels were only 20% and 30%, respectively. When the commercial mixture of atrazine + mesotrione was applied at the rate corresponding to 2000 g a.i. $ha^{-1}$ of atrazine, hairy fleabane control was approximately 75%, about 25% higher than that observed with atrazine alone at the same rate. The C50 value for atrazine was approximately 23-fold lower when the herbicide was mixed with mesotrione (Table 1), indicating the positive effect of adding the HPPD inhibitor for hairy fleabane control.

At 28 DAT, the application of the formulated atrazine + mesotrione mixture once again outperformed the atrazine applied alone in controlling hairy fleabane plants (Figure 1C). The average control was approximately 28% at the 500 g a.i. $ha^{-1}$ and 1000 g a.i. $ha^{-1}$ rates when atrazine was applied alone. However, when atrazine was applied at these same rates in a commercial mixture with mesotrione, the control increased to 78% and 83%, respectively. At 28 DAT, the atrazine C50 values were 1648 g a.i. $ha^{-1}$ for the application alone and 80.22 g a.i. $ha^{-1}$ for the application in a commercial mixture with mesotrione. In summary, the addition of mesotrione reduced the atrazine C50 value by more than 20-fold (Table 1).

At 35 DAT, the commercial mixture of atrazine + mesotrione provided satisfactory control of hairy fleabane plants, reaching 90% at the atrazine rates of 500 g a.i. $ha^{-1}$ and 1000 g a.i. $ha^{-1}$ (Figure 1D). However, at these same rates of atrazine applied alone, control levels were below 30%. Hairy fleabane control was high when the atrazine rate was increased to 2000 g a.i. $ha^{-1}$, reaching values around 85%. At the highest dose of the commercial atrazine + mesotrione mixture plant death was complete, as can be observed in Figure 2. The atrazine C50 values were 897.72 g a.i. $ha^{-1}$ for the application alone and 130.88 g a.i. $ha^{-1}$ for the application in a commercial mixture with mesotrione (Table 1). When mesotrione was applied alone, hairy fleabane control was around 55%, indicating poor control, similar to that of atrazine applied alone at its recommended doses.

Shoot fresh weight (SFW) and shoot dry weight (SDW) were also determined at 35 DAT. For both parameters, a reduction in the weight of hairy fleabane plants was observed as the applied atrazine dose increased (Figures 3A and 3B). However, as with the control, the atrazine + mesotrione mixture resulted in greater growth inhibition of hairy fleabane plants, leading to lower GR50 values (Table 1). This substantial reduction in GR50 values provided by the atrazine + mesotrione mixture demonstrates a significant increase in herbicide potency, implying that the presence of mesotrione allows for effective growth suppression at much lower doses of atrazine than would be required if applied individually. It is important to note that, for SDW, atrazine applied alone showed a lower goodness-of-fit to the log-logistic model, as reflected by a higher standard error in the GR50 estimate. This suggests a less predictable dose-response pattern for biomass reduction within the tested dose range when the herbicide is used without the synergistic effect of mesotrione.


**Figure 2.** Visual appearance of *Conyza* spp. plants at 35 days after treatment (DAT) subjected to different doses of (A) atrazine alone and (B) atrazine + mesotrione mixture. g a.i. $ha^{-1}$: grams of active ingredient per hectare. Treatments also included an untreated control (Check) and mesotrione alone (100 g a.i. $ha^{-1}$).

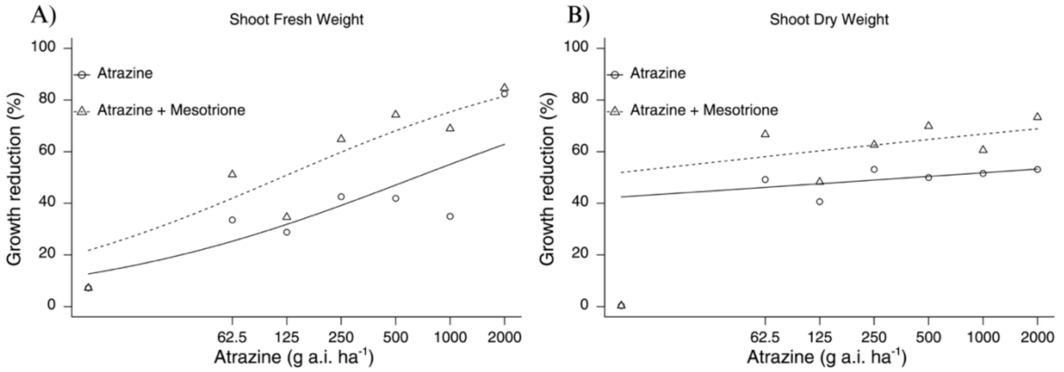


**Figure 3.** Growth reduction based on shoot fresh weight (SFW) (A) and shoot dry weight (SDW) (B) of hairy fleabane (*Conyza* spp.) at 35 days after treatment (DAT). g a.i. $ha^{-1}$: grams of active ingredient per hectare. Symbols represent observed means and lines represent the fitted three-parameter log-logistic model.

Colby's test was performed for the control assessments at 14 and 35 DAT, as well as for the SFW and SDW, using the recommended doses for the herbicides applied alone: atrazine (1000 g a.i. $ha^{-1}$) and mesotrione (100 g a.i. $ha^{-1}$); and for the formulated atrazine + mesotrione mixture (1000 g a.i. $ha^{-1}$ + 100 g a.i. $ha^{-1}$). Colby's method estimates a level of control based on observations from applications of the individual active ingredients. In all assessments, synergistic responses were observed for the atrazine + mesotrione mixture on hairy fleabane (Table 2). For the control at 35 DAT, the expected control calculated by Colby's method was only 68%, while the observed control was 91%, indicating synergism in the commercial mixture.

**Table 2.** Colby's test to assess the interaction between mesotrione (100 g a.i. $ha^{-1}$) and atrazine (1000 g a.i. $ha^{-1}$) for the control and growth reduction of hairy fleabane (*Conyza* spp.).

| Control | Observed control (%) | Expected control (%) | P-value | Response |
|---|---|---|---|---|
| 14 DAT | 63.3 | 34.0 | 0.0250 | Synergism |
| 35 DAT | 91.0 | 67.9 | 0.0228 | Synergism |
| Growth reduction | Observed reduction (%) | Expected reduction (%) | P-value | Response |
| Shoot Fresh Weight | 57.5 | 11.0 | 0.00784 | Synergism |
| Shoot Dry Weight | 38.2 | 24.0 | 0.0213 | Synergism |

DAT: days after treatment. The interaction was considered synergistic when the observed control/reduction was significantly higher than the expected value ($P < 0.05$).

Overall, the atrazine + mesotrione mixture was considerably superior to atrazine alone in the post-emergence control of hairy fleabane in all assessments conducted (Figure 1). Matte et al. (2018) also achieved satisfactory control with the commercial mixture of atrazine and mesotrione. In their study, hairy fleabane plants were completely controlled at 14 days after herbicide application at a dose of 500 g a.i. $ha^{-1}$ of atrazine and 50 g a.i. $ha^{-1}$ of mesotrione. In the same study, the commercial mixture also provided 100% control of the weeds *Commelina benghalensis*, *Bidens pilosa*, *Ipomoea grandifolia*, and *Urochloa plantaginea*. These results corroborate those of Albrecht et al. (2025), who observed that combining atrazine with mesotrione resulted in more effective control of *C. benghalensis* and grasses.

The results obtained here indicate synergy between atrazine and mesotrione (Table 2). Similarly, Fluttert et al. (2022a) demonstrated the efficacy of the atrazine-mesotrione combination in controlling glyphosate-resistant horseweed (*Conyza canadensis*). The herbicide mixture provided 100% control at 56 days after application (DAA), a result superior to the 87% and 31% control obtained with the mesotrione and atrazine applied alone, respectively. Based on Colby's method, the authors calculated that the efficacy of the commercial mixture exceeded the expected value by 11%, confirming the synergistic effect of the interaction. These findings corroborate the results obtained in the present study.

The synergism found in this study corroborates the results described by Kruse et al. (2001) for the control of *Bidens pilosa*. The authors reported synergism between atrazine and mesotrione, and between metribuzin and clomazone, both of which inhibit PSII and carotenoid synthesis, respectively. Early research also reported synergism between a mixture of photosystem II inhibitors and carotenoid-synthesis-inhibiting herbicides in controlling *Ipomoea hederacea* var. integriuscula (Westberg et al. 1989). Walsh et al. (2012) found synergy between atrazine and mesotrione, noting that the synergistic effect is more pronounced at low doses of both herbicides. In their studies, using doses equivalent to 0.5 g a.i. $ha^{-1}$ of mesotrione and 25 g a.i. $ha^{-1}$ of atrazine, weed mortality was less than 10% when the herbicides were used alone, and 47% when the two herbicides were applied together. Correia (2016) also confirmed a synergistic effect between mesotrione and atrazine in controlling *Merremia aegyptia*. When a mesotrione dose corresponding to 192 g $ha^{-1}$ was used, the control was approximately 37%; however, when the mixture of mesotrione (120 g $ha^{-1}$) + atrazine (1500 g $ha^{-1}$) was applied, the control of *Merremia aegyptia* was greater, with values equivalent to 98%, even at 120 DAA.

PSII-inhibiting herbicides interrupt electron transport in photosynthesis, causing an accumulation of energy in chlorophyll molecules and leading to the formation of free radicals, such as singlet oxygen ($1O_2$) and the hydroxyl radical (OH•). This excess energy causes oxidative stress, damaging cell membranes and resulting in plant death (Kruse et al., 2001). Naturally, plants possess a defense mechanism against this process, which involves carotenoid pigments that protect cells by dissipating excess energy (Sun et al., 2022). Therefore, combining a PSII inhibitor with an herbicide that inhibits carotenoid synthesis can result in synergism. This synergism is explained by reduced plant defenses due to inhibition of carotenoid synthesis, making it more vulnerable to oxidative stress induced by the PSII inhibitor (Kruse et al., 2001).

A second mechanism of synergism occurs when PSII inhibitors are combined with HPPD inhibitors. The inhibition of HPPD causes a simultaneous reduction in the levels of plastoquinone (PQ) and α-tocopherol. The depletion of PQ, the main competitor of PSII inhibitors (e.g., atrazine) for binding to the D1 protein, attenuates competition at this site. Consequently, the binding of the PSII-inhibiting herbicide to its target is enhanced, resulting in a more efficient inhibition of electron transport and, therefore, greater efficacy of the mixture (Traxler et al., 2023).

In addition, Chahal et al. (2019) found that the application of mesotrione with atrazine increased mesotrione absorption in *Amaranthus palmeri* compared with mesotrione alone, with values of 51% and 39% of the applied amount, respectively. However, atrazine absorption was not influenced by the addition of mesotrione to the mixture. This response appears to depend on the weed species and cuticle composition, since Silveira et al. (2020), based on radioisotope (14C) analyses, concluded that the synergism of the mixture in *Ipomoea hederifolia* is not related to greater absorption or translocation of the herbicides.

It should be noted that the type of interaction between herbicides and, consequently, the final efficacy on weeds, can also be affected by physicochemical characteristics, such as pKa and log Kow (Barbieri et al., 2022). These characteristics are important for the absorption and translocation of herbicides. Atrazine has physicochemical properties (log Kow = 2.7; pKa = 1.7, weak base) that confer limited translocation via the xylem and along the transpiration stream, with accumulation in older leaves (Silveira et al., 2020; PPDB, 2025). Mesotrione, on the other hand, is characterized as a weak acid (pKa = 3.12) with high hydrophilicity (log Kow = 0.11), which translocates via both xylem and phloem, reaching the growing points in the shoots (Silveira et al., 2020; PPDB, 2025). Thus, the effect of the herbicides is complementary, enhancing herbicide application efficacy, even at lower doses than the active ingredients applied alone. In the present study, atrazine was observed to act on the lower leaves of hairy fleabane, with symptoms of necrosis, whereas on the upper leaves and new shoots, symptoms of bleaching (albinism), characteristic of mesotrione, were observed (Figure 2).

The combination of these two mechanisms of action (PSII and HPPD inhibitors), in addition to synergism, also helps prevent and manage resistant weeds, including resistance to the triazine group, such as atrazine. This combination was effective in controlling atrazine-resistant *Raphanus raphanistrum* (Walsh et al., 2012) and also showed greater control when applied in post-emergence to *Amaranthus palmeri*, resistant both to HPPD and PSII inhibitors, rather than when applied alone (Chahal et al., 2018)

In addition to the aforementioned advantages, the addition of mesotrione to atrazine broadens the spectrum of control, especially on monocotyledonous species, with a synergistic action on this class of weeds. Maciel et al. (2013) found synergism between atrazine and mesotrione in controlling *Digitaria horizontalis*. They reported improved root and foliar absorption of the mixture by the plant compared with the isolated active ingredients. Other studies have also observed greater control of agronomically important grasses with the application of the atrazine + mesotrione mixture, such as in populations of *Eleusine indica* (Takano et al., 2018), *Echinochloa crus-galli*, *Digitaria sanguinalis* (Chhokar et al., 2019), and *Digitaria insularis* (Albrecht et al., 2025).

## 4. Conclusions

The commercial mixture of atrazine and mesotrione is effective in controlling hairy fleabane (*Conyza* spp.) at the recommended doses of 500 + 50 and 1000 + 100 g a.i. $ha^{-1}$ (atrazine + mesotrione). For atrazine applied alone, a dose of 2000 g a.i. $ha^{-1}$ was required to achieve satisfactory control.

The results confirm the existence of synergism between atrazine (a photosystem II inhibitor) and mesotrione (an HPPD inhibitor) for the post-emergence control of hairy fleabane. As a practical implication, the use of this commercial mixture is recommended as a strategic component of Integrated Weed Management (IWM) programs. It serves as an effective post-emergence tool to manage difficult-to-control populations and mitigate the selection of resistant biotypes by utilizing complementary modes of action (HPPD and PSII inhibition).

## Authors' Contribution

Conceptualization of the manuscript and development of the methodology: A.F.O.L., J.F.F., G.F., M.A.S.K. and G.D.; data collection and curation: A.F.O.L., J.F.F. and G.F.; data analysis: G.F. and M.A.S.K.; data interpretation: A.F.O.L., J.F.F., G.F., M.A.S.K. and G.D.; funding acquisition and resources: G.D.; project administration: G.D.; supervision: G.D.; writing the original draft of the manuscript: A.F.O.L., J.F.F., G.F., M.A.S.K. and G.D.; writing, review and editing: A.F.O.L., J.F.F., G.F., M.A.S.K. and G.D.; All authors read and agreed to the published version of the manuscript.

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