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WEED CONTROL EFFICIENCY AND SELECTIVITY OF PRE-EMERGENT HERBICIDES FOR GARLIC CROP

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Abstract
This study aimed to evaluate the efficiency and selectivity of pyroxasulfone and pyroxasulfone + flumioxazin at garlic cv. Ito pre-emergence. The experiment was conducted in two commercial areas in Curitibanos/SC during 2021 and 2022, using a randomized block design with four replications. The treatments consisted of the pre-emergence application of: pyroxasulfone at rates of 75, 100, and 125 g ha^{-1}; pyroxasulfone + flumioxazin at rates of 60 + 40, 90 + 60, and 120 + 80 g ha^{-1}; oxyfluorfen + flumioxazin (180 + 25 g ha^{-1}); pendimethalin + flumioxazin (1820 or 1600 + 25 g ha^{-1}); and pendimethalin alone (1820 or 1600 g ha^{-1}). In addition, we included an untreated and a weed-free control. This study evaluated weed density, dry mass, phytotoxicity, and bulb yields. In 2021, no weeds were reported in the cultivation area, thus only herbicide selectivity for garlic was evaluated, with all the treatments being selective without reducing the yield of garlic. In 2022, ryegrass and wild radish were predominant weeds in the crop, but the treatments caused a greater reduction in the number of ryegrass plants compared to wild radish. The plots with a higher number of wild radish plants showed a greater accumulation of dry mass due to their rapid development and large size. The most effective herbicides against these species were pyroxasulfone + flumioxazin at doses 60 + 40 and 120 + 80 g ha^{-1}, and oxyfluorfen + flumioxazin, while also giving a high total and commercial yield. Therefore, pyroxasulfone and pyroxasulfone + flumioxazin are selective treatments at garlic cv. Ito pre-emergence.

Keywords: *Allium sativum*. *Lolium multiflorum*. Pre-emergence. *Raphanus raphanistrum*.

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1. Introduction

Garlic (*Allium sativum*) is a highly important agricultural product in Santa Catarina State, with the Curitibanos region being the second-largest producer in Brazil (Gugel 2024). Being a highly sensitive crop, many factors can affect garlic cultivation, including weed interference. In Santa Catarina, some of the most common weed species impacting garlic are ryegrass (*Lolium multiflorum*), chickweed (*Stellaria media*), pigweed (*Amaranthus hybridus*), hair berggarticks (*Bidens pilosa*), dock (*Rumex* sp.), sow thistle (*Sonchus oleraceus*), wild radish (*Raphanus raphanistrum*), radish (*Raphanus sativus*), swinecress (*Coronopus didymus*), nutgrass (*Cyperus rotundus*), annual bluegrass (*Poa annua*), and signalgrass (*Urochloa plantaginea*) (Lucini 2009).

Garlic is particularly susceptible to weed interference due to its slow initial growth, narrow leaves, and low stature, which do not provide adequate ground coverage in comparison to the other plants (Resende et al. 2024). Therefore, competition for space, water, light, and nutrients is high throughout the crop cycle. When this competition increases, the bulb diameter and weight decrease, affecting the final yield and productivity (Marcuzzo and Santos 2021; Guerra et al. 2024). This is also noted in Singh et al. (2023), where the presence of weeds until harvest led to an 88% decrease in garlic yield, and in Aghabeige and Khodadadi (2017), where only weed-free garlic fields reached their maximum yield potential.

Consequently, to avoid these losses, producers opt for chemical weed control in cultivated areas, the most common being post-emergence herbicide application (Lucini 2009). However, there are a limited number of registered molecules at the post-emergence stage, especially for controlling dicotyledonous weeds, as there are only a few efficient herbicides appropriate for garlic cultivation (MAPA 2025).

To address this issue, pre-emergence molecules are generally used, as the use of herbicides at this stage prevents resource competition, avoiding yield and quality losses at harvest (Guerra et al. 2024). An alternative for pre-emergence control could be the active ingredient pyroxasulfone. Pyroxasulfone is currently recommended for crops such as peanuts, potatoes, coffee, sugarcane, barley, citrus fruits, eucalyptus, tobacco, sunflowers, corn, soybean, and wheat as it targets both grasses and broadleaf weeds with small seeds (Ihara 2024). Moreover, it can be used in combination with other active ingredients, such as flumioxazin. These herbicides are not yet registered for garlic, but they could be an excellent alternative for weed and crop management at pre-emergence.

Therefore, this study aims to evaluate the efficiency and selectivity of pre-emergence herbicides applied during garlic cultivation, focusing primarily on pyroxasulfone alone and in combination with flumioxazin.

2. Material and Methods

Two experiments were conducted at two garlic cultivation areas in the municipality of Curitibanos, Santa Catarina State, Brazil between July and November 2021 and 2022. The 2021 experiment was carried out at a latitude of 27°37’16.1’’ S, a longitude of 50°58’41.1’’ W, and an altitude of 906 m. Conversely, in 2022 the experiment was performed at a latitude of 27°29’81.1” S, a longitude of 50°69”29.5” W, and an altitude of 935 m. According to the Köppen classification, the climate in Curitibanos is temperate Cfb, humid mesothermal with mild summers. Here, the average annual precipitation is 1600 mm with an average temperature of 16.5 °C (Wrege et al. 2012). Figure 1 presents the total precipitation and the average, maximum, and minimum temperatures in Curitibanos, SC, during the experimental periods.

The soil in the experimental areas was classified as *Cambissolo*, according to the Brazilian Soil Classification System (SBCS) (Santos et al. 2018), which corresponds to *Inceptisols* in the U.S. Soil Taxonomy (EMBRAPA Solos 2025). Physical and chemical soil analysis, conducted in the 0-0.2 m layer, revealed that the soil used for the 2021 cultivation had a water pH of 6.3 and was composed of 58% clay, 29.4% silt, 12.6% sand, and 1.4% organic matter (OM). For the 2022 experiment, the soil was composed of 68% clay, 25.1% silt, 6.9% sand, and 3.3% OM with a pH of 5.7.

The experiments were conducted in a randomized block design with four replications each. Nine treatments at the pre-emergence of garlic and weeds involved herbicide application (Table 1). In 2021, only an untreated control (without any weed management) was used but in 2022 an additional control with manual weeding (weed-free control) was included.

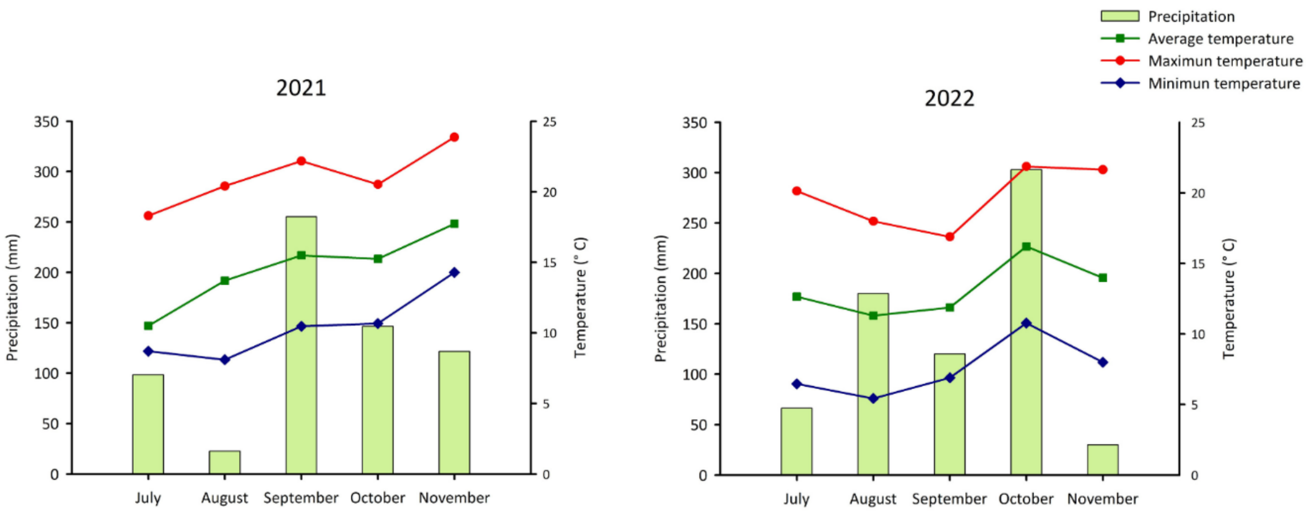

Figure 1. Precipitation (mm) and the average, maximum, and minimum temperatures (°C) in Curitibanos (SC) during the experimental periods of 2021 and 2022.

Table 1. Herbicide treatments, active ingredients, and applied doses at the pre-emergence stage of garlic cultivation. Curitibanos (SC), 2021 and 2022*.

Treatments	Active ingredient	Dose (g ha^{-1})
T1	PYR	75
T2	PYR	100
T3	PYR	125
T4	PYR + FLU	60 + 40
T5	PYR + FLU	90 + 60
T6	PYR + FLU	120 +80
T7	Oxyfluorfen + FLU	180 + 25
T8	PEN + FLU	1820/1600 + 25
T9	PEN	1820/1600
T10	Untreated control	-
T11	Weed-free control	-

*The PEN doses varied between years (1820 g ha^{-1} in 2021 and 1600 g ha^{-1} in 2022) due to the use of different pre-mixed products. PYR – pyroxasulfone, FLU – flumioxazin, PEN - pendimethalin

The commercial products used for each active ingredient were: Yamato® (pyroxasulfone 500 g L^{-1}, Ihara), Kyojin® (pyroxasulfone 300 g L^{-1} + flumioxazin 200 g L^{-1}, Ihara), Goal® (oxyfluorfen 240 g L^{-1}, Corteva), and Flumyzin® (flumioxazin 500 g L^{-1}, Ihara), Prowl H2O® (455 g L^{-1}, BASF) and Herbadox® (400 g L^{-1}, BASF) for pendimethalin in 2021 and 2022, respectively, resulting in a change in application dose.

For the experiment setup, the soil was prepared with plowing, harrowing, and ridging operations. The experimental plots consisted of three double planting rows spaced at 0.3 and 0.1 m between rows, with a planting density of 10 cloves per meter, and each plot covered an area of 3.25 m². Fertilization, cultural practices, and irrigation followed the management practices of the property, following recommendations for garlic cultivation in Santa Catarina.

In both years, the garlic cultivar used was Ito, a widely grown purple noble garlic variety in Brazil. In the first year, garlic was planted on July 02, 2021, with herbicide application five days later on July 7, 2021. For the second year of the experiment, garlic was planted on July 5, 2022, with herbicide application on the following day, July 6, 2022.

The herbicides were applied using a pressurized CO_2 backpack sprayer, at an application rate of 150 L ha^{-1}. Environmental conditions during application in 2021 were a temperature of 15.4°C, relative humidity (RH) of 67.8%, wind gusts until 1.5 km h^{-1}, and moist soil. For 2022, environmental conditions were 24.4°C temperature, RH of 52.8%, wind gusts until 1.5 km h^{-1}, with moist soil irrigated on the day of application. The weed-free control involved hand-weeding to promote garlic growth without weed interference, while the untreated control had no weed management to demonstrate the damage caused by weed interference to the crop.

In this study, we only evaluated the central double row of plots, excluding the outer rows, evaluating variables related to crop phytotoxicity and bulb yield. In 2022, we additionally evaluated the effect of herbicides on the density and dry weight of the emerged weeds.

For evaluating the phytotoxicity, assessments were conducted at 15, 30, and 45 days after herbicide application (DAA) using a visual rating scale ranging from 0 to 100%, where zero represents no symptoms and 100 represents plant death (Kuva et al. 2016). The assessment of weed density, only conducted in 2022, was done at 15, 30, and 70 DAA. Weeds within a 0.25 m² frame randomly placed in the useful area of each plot were identified and counted. At 70 DAA, weeds were manually collected from the useful area of each plot using a randomly placed square metal frame with an area of 0.25 m² to determine their dry weight. The collected weeds were stored in paper bags and dried in a forced air circulation oven at 55 ± 2 °C, and their dry weight was subsequently determined using a precision scale.

The bulbs present in the central double line of the plot were harvested and then cured in a protected environment. Once they reached the ideal curing point, the aerial part and root system of the plants were removed to carry out yield assessments on the bulbs. Bulbs were separated into commercial (bulbs diameter > 31 mm) and industrial (bulbs diameter > 31 mm) classes, extrapolating weight values per plot to estimate commercial bulb yield (bulbs > 31 mm) and total yield, as according to the *Portaria* nº. 435 of May 18, 2022, from the *Ministério da Agricultura, Pecuária e Abastecimento* – MAPA (MAPA 2022).

Data from the studied variables were subjected to analysis of variance using the F test, with a significance level of 5%. Subsequently, the data underwent the Scott Knott grouping test, again at 5% probability. All statistical analyses were performed using the SISVAR program (Ferreira 2019).

3. Results

In the 2021 season, only the effects of herbicides on the crop were evaluated in order to determine the herbicide selectivity under garlic cultivation. The phytointoxication assessments conducted at 15 and 30 DAA resulted in almost identical responses (Table 2). All doses of pyroxasulfone, its combination with flumioxazin at a rate of 60 + 40 g ha^{-1}, and pendimethalin (alone or in combination with flumioxazin) showed statistically equal results to the untreated control, where no herbicides were applied. Our observations showed that the combination of pyroxasulfone with flumioxazin had higher levels of phytotoxicity within the garlic compared to similar doses of pyroxasulfone alone. The highest levels of phytotoxicity were observed with oxyfluorfen + flumioxazin at 15 and 30 DAA and pyroxasulfone and flumioxazin (120 + 80 g ha^{-1}) at 15 and 30 DAA (17%, 20%, 19.25%, and 17.25%, respectively). However, at 45 DAA, all phytotoxicity values had decreased compared to 30 DAA, with the highest values seen with pyroxasulfone and flumioxazin at 120 + 80 g ha^{-1}, pyroxasulfone at 125 g ha^{-1}, and pyroxasulfone and flumioxazin at 90 + 60 g ha^{-1} (13.75%, 12.75%, and 10.75%, respectively). At 45 DAA, only pendimethalin applied alone, or in combination with flumioxazin, was statistically similar to the untreated control with 0 and 1.5% of plants showing damage, respectively (Table 2).

Table 2. Phytotoxicity (%) of garlic plants cv. Ito 15, 30, and 45 DAA of pre-emergence herbicide. Curitibanos (SC), 2021*.

Active ingrediente	Dose (g ha^{-1})	15 DAA	30 DAA	45 DAA
PYR	75	3.50^a	5.25^a	4.00^b
PYR	100	4.00^a	8.75^a	5.50^b
PYR	125	5.50^a	11.00^a	12.75^c
PYR + FLU	60 + 40	6.75^a	8.00^a	5.00^b
PYR + FLU	90 + 60	15.50^b	14.25^b	10.75^c
PYR + FLU	120 +80	19.25^b	17.25^b	13.75^c
Oxyfluorfen + FLU	180 + 25	17.00^b	20.00^b	6.25^b
PEN + FLU	1820 + 25	13.00^b	7.50^a	1.50^a
PEN	1820	2.25^a	4.00^a	0.00^a
Weed-free control	-	0.00^a	0.00^a	0.00^a
Coefficient of variation (%)		36.60	34.83	31.16

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. PYR – pyroxasulfone, FLU – flumioxazin, PEN - pendimethalin

In regard to yield, all treatments were statistically equal for commercial and total bulb yield with average yields of 10.3 to 12.5 thousand kg ha^{-1} and 9.15 to 11.36 thousand kg ha^{-1} for total and commercial bulbs, respectively (Figure 2).

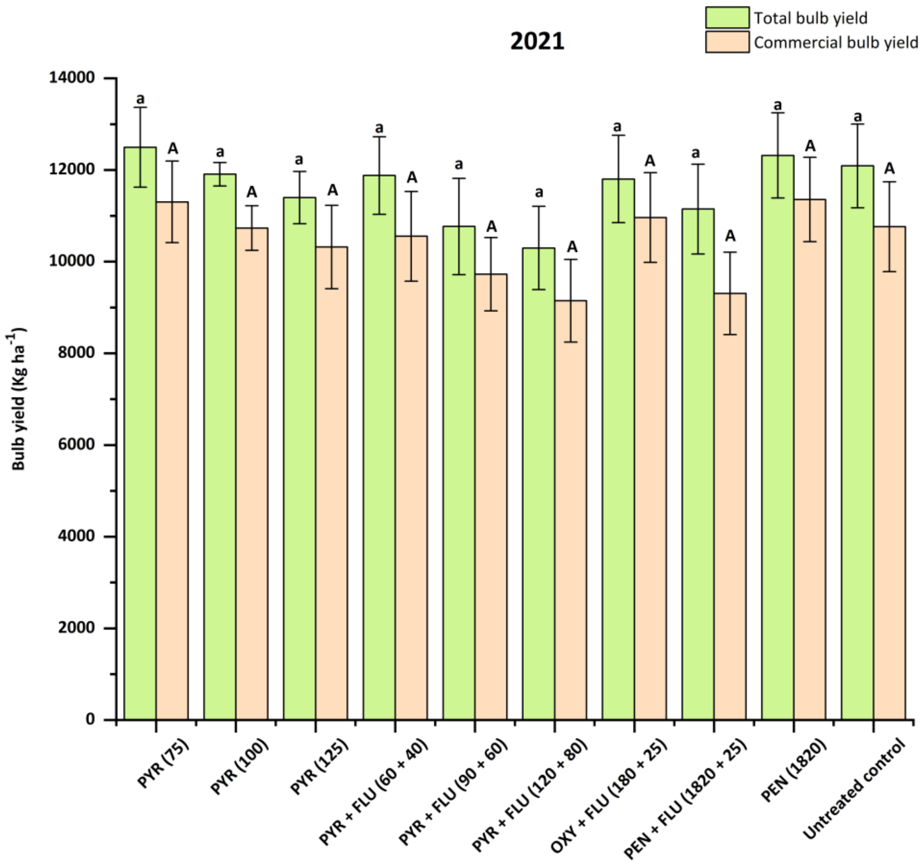

Figure 2. Total and commercial bulb yield of garlic (kg ha^{-1}) after herbicide application in pre-emergence. Curitibanos (SC), 2021*.

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. Lowercase letters are used for total bulb yield and uppercase letters are used for commercial bulb yield. PYR (75), pyroxasulfone 75 g ha^{-1}; PYR (100), pyroxasulfone 100 g ha^{-1}; PYR (125), pyroxasulfone 125 g ha^{-1}; PYR + FLU (60 + 40), [pyroxasulfone + flumioxazin 60 + 40 g ha^{-1}]; PYR + FLU (90 + 60), [pyroxasulfone + flumioxazin 90 + 60 g ha^{-1}]; PYR + FLU (120 + 80), [pyroxasulfone + flumioxazin 120 + 80 g ha^{-1}]; OXY + FLU (180 + 25), oxyfluorfen + flumioxazin (180 + 25 g ha^{-1}); PEN + FLU (1820 + 25), pendimethalin + flumioxazin (1820 + 25 g ha^{-1}); PEN (1820), pendimethalin (1820 g ha^{-1}).

After verifying the selectivity of herbicide treatments for garlic in the 2021 season, a study was conducted in the following season (2022) to evaluate the efficiency of these herbicides in controlling weeds. During the evaluation period in 2022, two weed species predominated in the cultivation area: ryegrass and wild radish. The evaluation of the number of ryegrass and wild radish plants started at 15 DAA. In this assessment, the formulated mixture of pyroxasulfone and flumioxazin showed great effectiveness against ryegrass at all doses, with weed numbers similar to those in the weed free control (Figure 3).

As for the wild radish plants, only two treatments were effective: pyroxasulfone + flumioxazin (120 + 80 g ha^{-1}) and oxyfluorfen + flumioxazin, with zero plants found, compared to the 23 plants m^{-2} found in the untreated control (Figure 3).

At 30 DAA, there was a decrease in ryegrass plants in plots treated with pyroxasulfone at doses of 100 and 125 g ha^{-1}, with zero plants m^{-2}, equaling the efficacy of pyroxasulfone + flumioxazin and the weed-free control. The application of pendimethalin alone and its mixture with flumioxazin showed the lowest effectiveness. However, they still led to a reduction of about 50% in ryegrass infestation. Regarding wild radish, only pyroxasulfone + flumioxazin at the highest dose was equivalent to the weed-free control, with one plant m^{-2}. The highest infestations were still observed with the pyroxasulfone treatment (75 and 100 g ha^{-1}) and were similar to the untreated control (Figure 3).

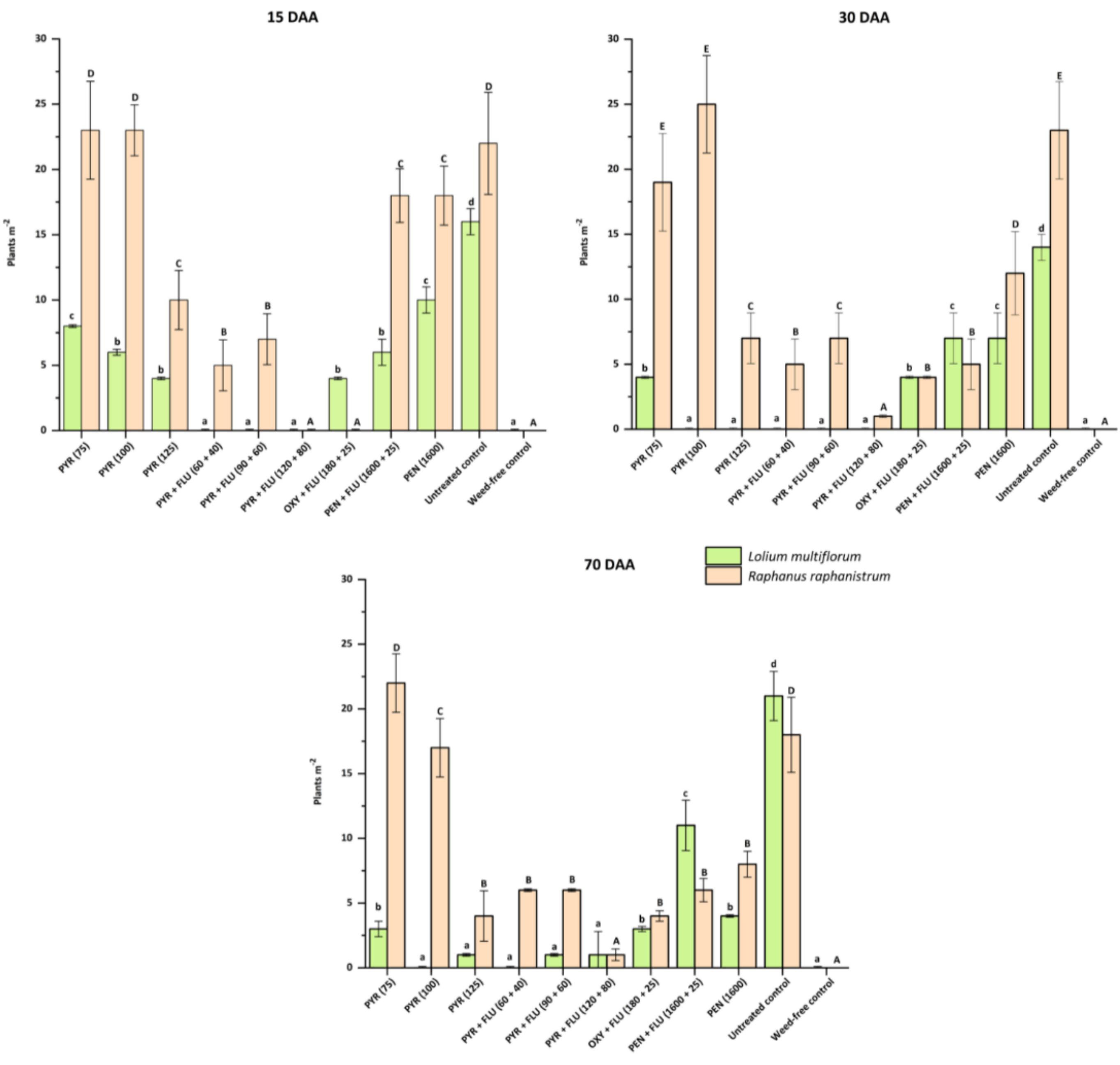

Figure 3. Number of ryegrass (*Lolium multifiorum*) and wild radish (*Raphanus raphanistrum*) plants m^{-2} at 15, 30, and 70 DAA after pre-emergence herbicide application, Curitibanos (SC), 2022*.

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. Lowercase letters are used for ryegrass and uppercase letters are used for wild radish. PYR (75), pyroxasulfone 75 g ha^{-1}; PYR (100), pyroxasulfone 100 g ha^{-1}; PYR (125), pyroxasulfone 125 g ha^{-1}; PYR + FLU (60 + 40), [pyroxasulfone + flumioxazin 60 + 40 g ha^{-1}]; PYR + FLU (90 + 60), [pyroxasulfone + flumioxazin 90 + 60 g ha^{-1}]; PYR + FLU (120 + 80), [pyroxasulfone + flumioxazin 120 + 80 g ha^{-1}]; OXY + FLU (180 + 25), oxyfluorfen + flumioxazin (180 + 25 g ha^{-1}); PEN + FLU (1600 + 25), pendimethalin + flumioxazin (1600 + 25 g ha^{-1}); PEN (1600), pendimethalin (1600 g ha^{-1}).

There were no changes in this trend between the second and final assessment at 70 DAA (Figure 4). During this time the number of weed plants m^{-2} in the untreated control had increased to 39. In regard to the dry mass of the weeds, only pyroxasulfone + flumioxazin (60 + 40 and 120 + 80 g ha^{-1}), and oxyfluorfen + flumioxazin treatments were statistically equal to the weed-free control. On the other hand, the untreated control had the highest weed dry mass accumulation, reaching 75.88 g m^{-2} (Figure 4). The herbicide treated plots with the highest dry mass were those with the highest number of wild radish plants.

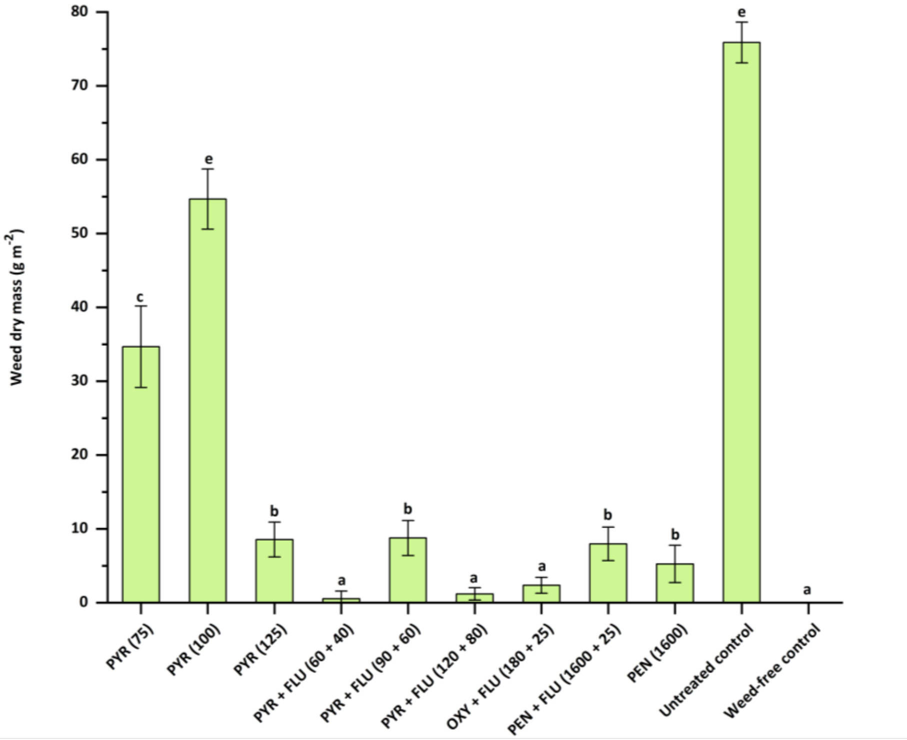

Figure 4. Weed dry matter (g m^{-2}) at 70 DAA of pre-emergence herbicide application. Curitibanos (SC), 2022*.

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. PYR (75), pyroxasulfone 75 g ha^{-1}; PYR (100), pyroxasulfone 100 g ha^{-1}; PYR (125), pyroxasulfone 125 g ha^{-1}; PYR + FLU (60 + 40), [pyroxasulfone + flumioxazin 60 + 40 g ha^{-1}]; PYR + FLU (90 + 60), [pyroxasulfone + flumioxazin 90 + 60 g ha^{-1}]; PYR + FLU (120 + 80), [pyroxasulfone + flumioxazin 120 + 80 g ha^{-1}]; OXY + FLU (180 + 25), oxyfluorfen + flumioxazin (180 + 25 g ha^{-1}); PEN + FLU (1600 + 25), pendimethalin + flumioxazin (1600 + 25 g ha^{-1}); PEN (1600), pendimethalin (1600 g ha^{-1}).

Regarding crop phytotoxicity, in the 2022 season, it was observed that injury levels were lower than the previous year at all dates observed (Table 3). At 15 DAA, all herbicides caused damage to the garlic plants, but all values were below 8.75%. Among these treatments, the isolated applications of pyroxasulfone, regardless of the dose, were the least harmful (between 3.0% and 2.50%). By 30 DAA, the maximum phytotoxicity among treatments was 6.25%. At the last evaluation (45 DAA), all the treatments had reduced in garlic phytotoxicity, showing between 1.5 to 3.5% phytotoxicity. Pyroxasulfone at all doses showed no injuries, as did pendimethalin and in combination with flumioxazin.

Table 3. Phytotoxicity (%) of garlic plants cv. Ito 15, 30 and 45 DAA of pre-emergence herbicide. Curitibanos (SC), 2022*.

Active ingrediente	Dose (g ha^{-1})	15 DAA	30 DAA	45 DAA
PYR	75	3.00^{b}	4.75^{c}	0.00^{a}
PYR	100	3.00^{b}	4.00^{c}	0.00^{a}
PYR	125	2.50^{b}	4.50^{c}	0.00^{a}
PYR + FLU	60 + 40	4.75^{c}	4.00^{c}	1.50^{b}
PYR + FLU	90 + 60	4.50^{c}	3.25^{b}	3.00^{c}
PYR + FLU	120 +80	5.50^{d}	6.25^{d}	3.25^{c}
Oxyfluorfen + FLU	180 + 25	8.75^{e}	5.50^{d}	3.50^{c}
PEN + FLU	1600 + 25	8.25^{e}	4.50^{c}	3.25^{c}
PEN	1600	4.00^{c}	2.75^{b}	0.00^{a}
Untreated control	-	0.00^{a}	0.00^{a}	0.00^{a}
Weed-free control	-	0.00^{a}	0.00^{a}	0.00^{a}
Coefficient of variation (CV. %)		21.19	20.40	34.81

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. PYR – pyroxasulfone, FLU – flumioxazin, PEN – pendimethalin

In 2022, comparison of the untreated and weed-free controls showed that the co-cultivation of garlic with weeds led to a 17% yield reduction (Figure 5). Applications of pyroxasulfone, at all doses, along with pendimethalin and flumioxazin gave similar yields to the untreated control, ranging from 9.49 to 10.40 thousand kg ha^{-1}.

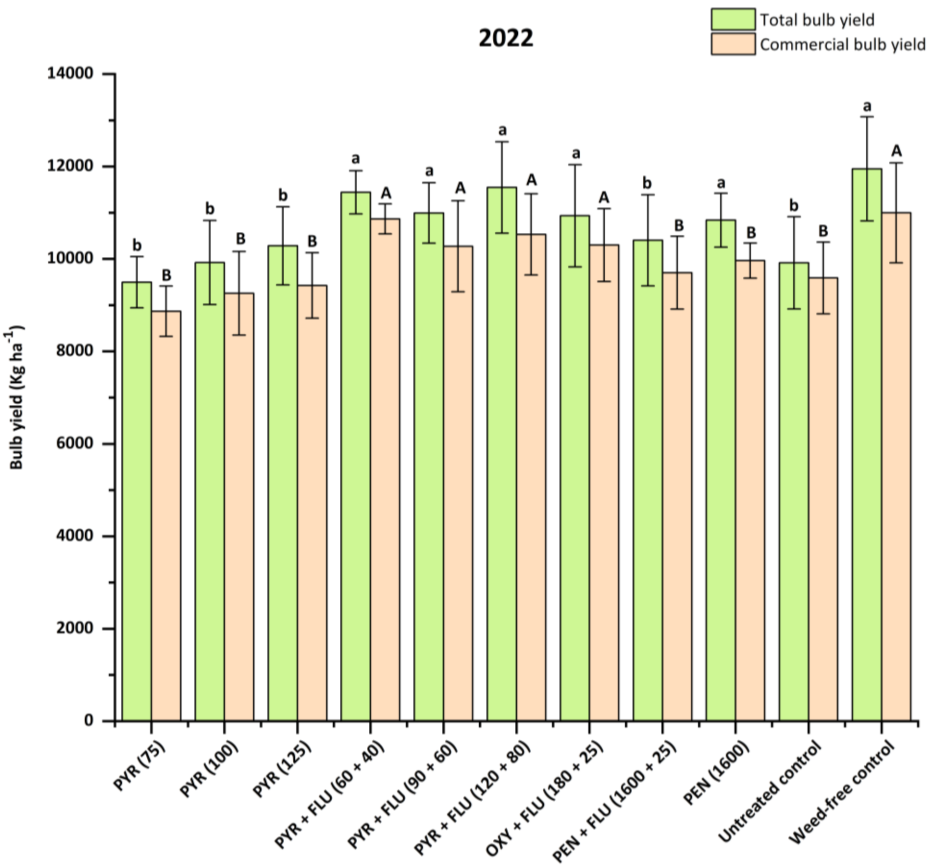

Figure 5. Total and commercial bulb yield of garlic (kg ha^{-1}) after pre-emergence herbicide application. Curitibanos (SC), 2022*.

*Means followed by the same letter in the column do not differ significantly according to the Scott Knott test, at a 5% probability level. Lowercase letters are used for total bulb yield, and uppercase letters are used for commercial bulb yield. PYR (75), pyroxasulfone 75 g ha^{-1}; PYR (100), pyroxasulfone 100 g ha^{-1}; PYR (125), pyroxasulfone 125 g ha^{-1}; PYR + FLU (60 + 40), [pyroxasulfone + flumioxazin 60 + 40 g ha^{-1}]; PYR + FLU (90 + 60), [pyroxasulfone + flumioxazin 90 + 60 g ha^{-1}]; PYR + FLU (120 + 80), [pyroxasulfone + flumioxazin 120 + 80 g ha^{-1}]; OXY + FLU (180 + 25), oxyfluorfen + flumioxazin (180 + 25 g ha^{-1}); PEN + FLU (1600 + 25), pendimethalin + flumioxazin (1600 + 25 g ha^{-1}); PEN (1600), pendimethalin (1600 g ha^{-1}).

The highest total yield was observed in treatments with lower weed infestations, except for the combination of pyroxasulfone and flumioxazin at 90 + 60 g ha^{-1} and pendimethalin, which also showed statistical equivalence with the others. Therefore, herbicides that reduced the number of weeds increased both the commercial and total garlic bulb yields as they reduced competition for environmental resources (Figure 5). Once again, the best herbicides (same from previous evaluation) resulted in the highest commercial yields, between 10.27 and 10.99 thousand kg ha^{-1}.

4. Discussion

Evaluation of the 2021 season

Pendimethalin is a herbicide already registered for use on garlic (MAPA 2025) and is widely used for pre-emergence weed control in commercial garlic fields in Santa Catarina (Lucini 2009). The initial phytotoxicity assessments indicated that the application of pyroxasulfone alone and its combination with flumioxazin at 60 + 40 g ha^{-1} resulted in injuries similar to those caused by pendimethalin. This similarity suggests that garlic is tolerant to pyroxasulfone alone and its mixture with flumioxazin. This is similar to findings in studies looking at the use of pyroxasulfone and flumioxazin on onions and garlic pre- and post-emergence (Aghabeigi and Khodadadi, 2017; Bordignon et al. 2024).

Higher damage levels were seen with oxyfluorfen in combination with flumioxazin, and this is explained by their mechanism of action. These active ingredients act as protoporphyrinogen oxidase

(PROTOX) inhibitors, causing desiccation and photobleaching in the plant (Singh and Tiwari 2020). Thus, due to the overload of protoporphyrinogens, the garlic plants could not metabolize them immediately, prolonging the manifestation of toxic effects.

Flumioxazin applied pre-emergence (40 g ha^{-1}) initially caused phytotoxicity in the garlic plants, with the damage decreasing over time, indicating the plant's ability to metabolize these molecules and eventually recover (Guerra et al. 2020). Flumioxazin is presently registered for use in garlic, among other crops (MAPA 2025). However, higher doses of flumioxazin can cause severe damages to the crop (Oliveira Júnior and Inoue 2011), and this was seen here in its combination with pyroxasulfone where increasing doses led to increased phytotoxicity. In onions, pre-emergence application of flumioxazin at 153 g ha^{-1} causes drastic reductions in bulb weight in sandy soil areas (López-Urquídez et al. 2020).

While some phytotoxicity and plant damage were noted in the 2021 season, there was no negative impact on commercial and total bulb yield, indicating that the herbicide treatments applied at the pre-emergence stage were selective for garlic cv. Ito. This response is very important because pyroxasulfone alone, as well as pyroxasulfone + flumioxazin, are not yet registered for garlic cultivation.

Evaluation of the 2022 season

Ryegrass and wild radish were the predominating weed species in our plots and are common in Santa Catarina State. They are annual winter species (Franceschetti et al. 2019; Pasquali and Barcaccia 2020), which coincides with the planting period of garlic in Brazil between June and July.

At 15 DAA, the untreated control already exhibited a high number of weeds per meter. The critical period for garlic begins at around 3 to 5 days after planting and extends up to 126 days for the varieties used in Santa Catarina, indicating the low competitive ability of this crop (Guerra et al. 2024). The weed infestation intensified over time, reaffirming the need for weed control pre-emergence to prevent plant growth that leads to competition with the crop.

Pyroxasulfone alone was not effective in decreasing the number of wild radish plants per square meter, as it is effective against grasses and broadleaf weeds with small seeds (Presoto 2022; Ihara 2024). This also explains its superior efficacy in ryegrass control compared to wild radish, as even at a dose of 100 g ha^{-1}, where the reduction in ryegrass numbers was equivalent to hand-weeding.

Therefore, to additionally control wild radish, flumioxazin must be used in combination with pyroxasulfone. Flumioxazin has a broad mechanism of action against broadleaf weeds pre-emergence, and so the combination leads to a broad action against weeds, reducing the competition in the field (Bordignon et al. 2024).

The mixture of pyroxasulfone and flumioxazin has been demonstrated to act synergistically, effectively controlling species such as guinea grass (*Panicum maximum*) at doses of 100 + 50 g ha^{-1} (Presoto et al. 2022), waterhemp (*Amaranthus tuberculatus*) at doses of 89 + 70 g ha^{-1} (Ferrier et al. 2022), ladysthumb (*Polygonum persicaria*), gallant soldier (*Galinsoga parviflora*), swine cress (*Coronopus didymus*), and wild radish at doses of 60 + 40, 75 + 50 and 90 + 30 g ha^{-1} (Bordignon et al. 2024). Pyroxasulfone alone and in combination with flumioxazin exhibit residual effects beyond 90 days after application (DAA) in clay-textured soil, as used in the present study (Novais et al. 2023).

In plots where herbicide applications were ineffective, there was a higher number of weeds. Among these infested plots, wild radish predominated over ryegrass. This weed has a rapid initial growth, drought tolerance, along with a high competitive capacity and its longevity (Franceschetti et al. 2019). This is in addition to factors such as high seed production, seed dormancy, and genetic and phenotypic variability. All of these factors combined mean it is difficult to control this species (Kebaso et al. 2020). Previous studies have shown that wild radish was more detrimental to onion than with ryegrass, leading to greater reductions in height, stem diameter, leaf area, and dry mass of the above-ground part of the onion (Franceschetti et al. 2019). These results align with the current study.

The 2022 phytotoxicity assessment revealed a reduction in garlic injury compared to 2021. We suggest that this seasonal variation is due to the environmental conditions before and/or after their application (Oliveira Júnior and Inoue 2011).

When evaluating garlic bulb yield, it becomes clear that weed presence significantly impacts crop growth, with yield reductions up to 46.5% in untreated versus weed-free plots (Siddhu et al. 2018; Ganapathi et al. 2020). By reducing the number of weeds, the competition between the garlic and weeds decreases, allowing the garlic bulbs to develop more effectively and reach their maximum growth potential (Guerra et al. 2024). As garlic is sold in grades according to its diameter, decreases in bulb yield will lead to decreases in the producer's profits. Therefore, it is crucial to control weeds in the cultivation area to avoid yield losses that will reflect in monetary losses.

The analysis from this study shows that herbicides can act differently on the garlic cultivated and the invading weeds. Weed control for ryegrass and wild radish varied among treatments, which is confirmed by the accumulation of dry matter in the plots. The herbicides that provided the best weed control allowed the garlic plants to establish and develop better, demonstrating their selectivity and positive impacts on yield. This emphasizes the relevance of using pre-emergence herbicides and highlights the combination of pyroxasulfone + flumioxazin as a new effective alternative for early weed control in garlic cultivation without affecting the yield.

5. Conclusions

Pyroxasulfone at 100 and 125 g ha^{-1} and pyroxasulfone + flumioxazin at all doses were effective in controlling ryegrass. For wild radish, only pyroxasulfone + flumioxazin at 120 + 80 g ha^{-1} and pendimethalin achieved effective control. Pyroxasulfone + flumioxazin (all doses) and oxyfluorfen + flumioxazin reduced the accumulation of dry weed matter, resulting in higher total and commercial bulb yield. All the herbicides tested were selective for garlic cv. Ito.

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