

Weed control efficacy and garlic crop selectivity under post-emergence applications of single and combined herbicides

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Abstract

Garlic production is severely constrained by weed interference throughout its growth cycle. Given the scarcity of research on chemical weed control in this vegetable crop, the present study evaluated the efficacy of post-emergence herbicide applications against broadleaf weed species (*Raphanus raphanistrum*, *Coronopus didymus*, *Stellaria media*, and *Rumex obtusifolius*), as well as their selectivity to garlic plants, by assessing plant height, stand, phytotoxicity, and bulb diameter and yield. The herbicides tested were ioxynil (75 g ha⁻¹), ioxynil + pendimethalin (75 + 1,820 g ha⁻¹), ioxynil + pyroxasulfone (75 + 100 g ha⁻¹), fomesafen (37.5 and 75 g ha⁻¹), S-metolachlor + fomesafen (258.9 + 56.9 g ha⁻¹), and prometryn (250 g ha⁻¹). The experiment was conducted in garlic commercial fields in Curitibaanos, Santa Catarina, Brazil, using a randomized block design with nine treatments, including two controls (hand-weeded and non-weeded), and four replications. Fomesafen (37.5 and 75 g ha⁻¹), S-metolachlor + fomesafen, and prometryn exhibited poor weed-control efficacy and low crop selectivity, resulting in high phytotoxicity, reduced bulb diameter, and significant yield losses. In contrast, ioxynil alone and mixed with pendimethalin or pyroxasulfone provided significant control of all target weed species and high selectivity to the garlic crop. These combinations, therefore, are promising and safe alternatives to the single post-emergence application of ioxynil in garlic crops.

Keywords: *Allium sativum*, broadleaf weed control, phytotoxicity, selectivity, yield

Introduction

Garlic, *Allium sativum* L. (Amaryllidaceae), is one of the most widely cultivated and consumed vegetable crops worldwide. It is characterized by slow initial growth and narrow, erect leaves, which result in low competitive ability against weeds (Lucini, 2009). Weed interference occurs throughout nearly the entire crop cycle, as many weed species emerge and develop simultaneously with garlic plants, competing directly for environmental resources (Raoofi et al., 2016; Zahadipour et al., 2023).

Beyond the competition for water, light, nutrients, and space, weeds release allelochemicals that can inhibit the growth of cultivated plants (Hijano et al., 2021). Their presence also makes mechanical harvesting challenging, often causing physical injury to bulbs during uprooting and damaging the primary commercially valuable structure (Guerra et al., 2020; 2022; 2024). Moreover, weeds serve as alternative hosts for numerous

pests and pathogens, significantly increasing the risk and severity of diseases in garlic crops (Oliveira & Briguenti, 2011).

In this context, weed development negatively affects both production and yield components by reducing bulb diameter and, consequently, the commercial value of the harvested product, with direct economic impact on growers (Pazinato, 2025). Factors such as low bulb weight, excessive number of cloves per bulb, and physiological disorders significantly decrease the market value of the crop (MAPA, 2022).

Furthermore, the bacterium *Pseudomonas marginalis* pv. *marginalis*, the causal agent of bacterial blight—a disease that causes severe losses in garlic production—can survive for up to five months in weed hosts, particularly dicotyledonous species, which then function as primary inoculum sources for subsequent infections (Marcuzzo & Santos, 2021).

The high susceptibility of garlic crops to weed interference can result in yield losses as high as 94.8% when competition is uncontrolled (Sahoo et al., 2018). It is important that the critical weed-free period for garlic extends from the 6th to the 126th day after emergence, encompassing nearly the entire productive cycle (Guerra et al., 2024).

Therefore, effective weed control is essential for successful garlic production, and herbicide use is a central management strategy. However, garlic plants exhibit significant sensitivity to herbicidal compounds, and crop injury is frequently observed (Guerra et al., 2022). Additionally, there is a limited availability of herbicides, especially post-emergence products, registered for broadleaf weed control in garlic cultivation in Brazil; currently, only ioxynil, linuron, and oxadiazon are officially approved for application to this crop (Agrofit, 2025).

Thus, the objective of this study was to evaluate the efficacy of post-emergence herbicide applications against eudicotyledonous weeds in garlic, while simultaneously assessing their selectivity to the crop. Given the inherent sensitivity of garlic plants, identifying active ingredients or mixtures that provide effective weed control with minimal phytotoxicity is essential for sustainable weed control management in this crop.

Material and methods

Experimental Area

The experiments were conducted in commercial garlic fields located in Curitibanos, Santa Catarina, Brazil, during the 2023 and 2024 growing seasons (July to November). In 2023, the experimental site was located at 27°15'35"S, 50°36'13"W, and an altitude of approximately 1,000 m. In 2024, the site was located at 27°18'05.38"S,

50°41'24.53"W, and an altitude of 920 m. The region's climate is Cfb (humid subtropical), according to the Köppen classification, with mild summers and a mean annual rainfall of approximately 1,500 mm (EMBRAPA, 2011).

The soils at both experimental areas were classified as Cambissolos Háplicos (Santos et al., 2025), corresponding to Hapludepts (Soil Survey Staff, 2022). Physical and chemical properties of the 0–20 cm soil layer are shown in **Table 1**.

Soil preparation in the experimental areas followed the conventional tillage system traditionally used for garlic in the region, consisting of plowing, harrowing, and the formation of raised beds. In 2023, garlic planting was performed on July 25 using the purple noble cultivar 'Ito', characterized by a long cycle in southern Brazil and producing 8–11 cloves per bulb (Resende & Pereira, 2012). In 2024, the planting was performed on July 02 using the white noble cultivar 'Quitéria', a late-cycle cultivar that forms 7–12 cloves per bulb and exhibits a rounded bulb shape (Resende et al., 2016).

Garlic cloves were planted manually in both growing seasons, arranged in three double rows per bed, with 0.30 m between beds and 0.10 m × 0.10 m spacing between cloves. Each plot measured 1.20 m × 2 m (2.4 m²). All cultural practices and fertilizer applications followed the technical recommendations for garlic cultivation in Santa Catarina (Lucini, 2009)

Experimental Design and Treatments

The experiments were conducted in a randomized block design with nine treatments and four replications. Each block consisted of a single raised bed. The post-emergence herbicide treatments consisted of

Table 1. Physical and chemical properties of the 0–20 cm soil layer after experiment establishment in the 2023 and 2024 garlic growing seasons.

Growing season	Clay %	OM g dm ⁻³	pH _(H₂O)	BS %	P mg dm ⁻³	CEC	K	Ca cmol _c dm ⁻³	Mg	Al
2023	87.0	14.00	6.3	87.74	3.0	10.05	0.716	7.29	2.04	0.00
2024	85	23.00	5.2	70.28	16.4	9.51	0.693	5.87	2.65	0.03

OM = organic matter; BS = base saturation; CEC = effective cation exchange capacity. Source: Soil analysis report – Soil Laboratory of Santa Catarina State University (LAS/CAV/ UDESC).

Table 2. Weather conditions recorded at the time of herbicide treatment applications during the 2023 and 2024 garlic growing seasons.

Growing season	Application date	Time	Temperature (°C)	Relative humidity (%)	Wind speed (km h ⁻¹)	Garlic leaf stage
2023	Aug 16	10:00	21.9	56.3	8.5	3 leaves
	Sep 01	07:50	14.4	79.2	10.0	5 leaves
	Sep 22	07:30	28.9	50.0	0.6	7 leaves
2024	Jul 26	08:50	20.5	60.5	3.0	3 leaves
	Aug 07	08:40	20.4	63.1	3.9	5 leaves
	Sep 23	08:30	28.0	55.3	0.8	7 leaves

ioxynil (75 g a.i. ha⁻¹), ioxynil + pendimethalin (75 + 1,820 g a.i. ha⁻¹), ioxynil + pyroxasulfone (75 + 100 g a.i. ha⁻¹), fomesafen (37.5 g a.i. ha⁻¹), fomesafen (75 g a.i. ha⁻¹), S-metolachlor + fomesafen (258.9 + 56.9 g a.i. ha⁻¹), and prometryn (250 g a.i. ha⁻¹). Additionally, two controls were tested: hand-weeded treatment, maintaining weed-free throughout the cycle to represent the reference condition for maximum attainable bulb yield; and non-weeded treatment, used as the reference for weed-control percentage evaluations.

Herbicide treatments were applied three times per growing season, the first at 20 days after planting (DAP) when garlic plants were at phenological stage 113, the second at 37 DAP (stage 115), and the third at 66 DAP (stage 117), following the BBCH scale described by Lopez-Bellido et al. (2016). Applications were carried out using a CO₂-pressurized backpack sprayer equipped with XR110015 flat-fan nozzles spaced 0.50 m apart, operated at 2 bar and a working speed of 1 m s⁻¹ providing a spray volume of 150 L ha⁻¹. Weather conditions during each application (Table 2) were recorded using a digital thermo-hygro-anemometer-luxmeter (model Skthal-01).

Evaluations

Weed control and crop phytotoxicity were visually assessed at 15 days after each of the three herbicide applications using the 0–100% scale described by Kuva et al. (2016). For weed control, 0% represented no visible injury and 100% indicated complete plant death. For phytotoxicity, 0% corresponded to the absence of symptoms on garlic plants and 100% to complete plant

death.

In 2023, *Raphanus raphanistrum* was the dominant weed species. In 2024, the weed community consisted of *R. raphanistrum*, *Coronopus didymus*, *Stellaria media*, and *Rumex obtusifolius*.

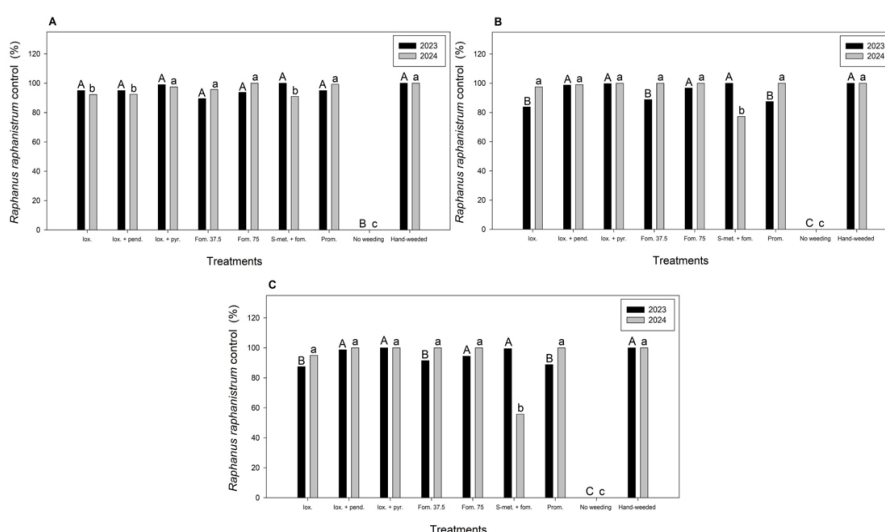
Immediately prior to garlic harvest (November 21, 2023, and November 7, 2024), plant height and final stand were recorded. Height was measured on five randomly selected plants per plot and averaged. Final stand was determined by counting the number of plants in a 1-m section of each of the two central rows per plot and calculating the mean. The plants used for stand assessment were then harvested, transferred to a greenhouse, and placed on slatted benches for curing. After curing, aerial part and roots were removed, and bulbs were graded according to the transverse diameter classes established by the Brazilian Ministry of Agriculture Ordinance No. 435 of May 2022 (MAPA, 2022), and then the bulb yield was determined by summing the bulbs of each class.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) and, when significant, treatment means were grouped using the Scott–Knott clustering test at the 5% probability level. All statistical analyses were performed using the statistical software Sisvar.

Results and Discussion

Figure 1 shows the percentage control of *Raphanus raphanistrum* 15 days after each of the three post-emergence herbicide applications during the 2023



Uppercase letters indicate the 2023 season, and lowercase letters indicate the 2024 season. Bars followed by the same uppercase or lowercase letter do not differ significantly according to the Scott–Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom.), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 1. Percentage control (%) of *Raphanus raphanistrum* 15 days after the first (A), second (B), and third (C) post-emergence herbicide applications in garlic crops during the 2023 and 2024 growing seasons, Curitiba, SC, Brazil.

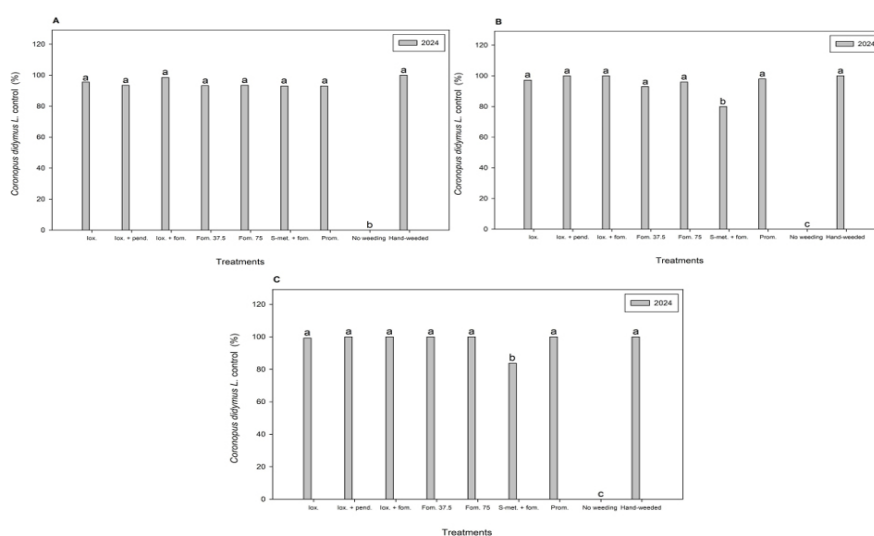
and 2024 garlic growing seasons. In 2023, all herbicides achieved satisfactory control (> 80%) by the final evaluation at 15 days after the third application (Figure 1C). However, treatments with ioxynil applied alone, fomesafen (37.5 g ha⁻¹), and prometryn exhibited slightly lower efficacy (87.5–91.5%), whereas the remaining treatments provided control > 94% and did not differ significantly from the hand-weeded control. In 2024, control of *R. raphanistrum* exceeded 95% for all herbicide treatments except the S-metolachlor + fomesafen mixture (55.75%) after the three applications (Figure 1C).

Coronopus didymus, *Rumex obtusifolius*, and *Stellaria media* were present only in the 2024 growing

season.

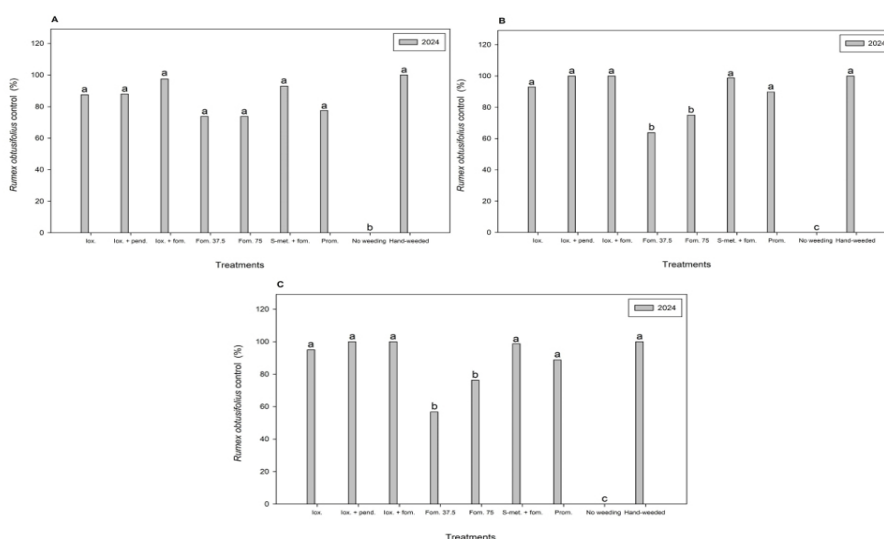
Most herbicides provided effective control of *C. didymus*, achieving ≥ 80% across all evaluations. S-metolachlor + fomesafen was the only treatment significantly inferior to the others, resulting in 83.75% control even after the third application, whereas all remaining herbicide treatments provided excellent control (> 99%) (Figure 2C).

Fomesafen applied alone (both 37.5 and 75 g ha⁻¹) resulted in the lowest control efficacy against *R. obtusifolius*, with control ranging from 56.75% to 76.75%. All other herbicide treatments provided ≥ 88.75% control of this species (Figure 3C).



Bars followed by the same letter do not differ significantly according to the Scott-Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 2. Percentage control (%) of *Coronopus didymus* 15 days after the first (A), second (B), and third (C) post-emergence herbicide applications in garlic crops during the 2024 growing season, Curitiba, SC, Brazil.



Bars followed by the same letter do not differ significantly according to the Scott-Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 3. Percentage control (%) of *Rumex obtusifolius* 15 days after the first (A), second (B), and third (C) post-emergence herbicide applications in garlic crops during the 2024 growing season, Curitiba, SC, Brazil.

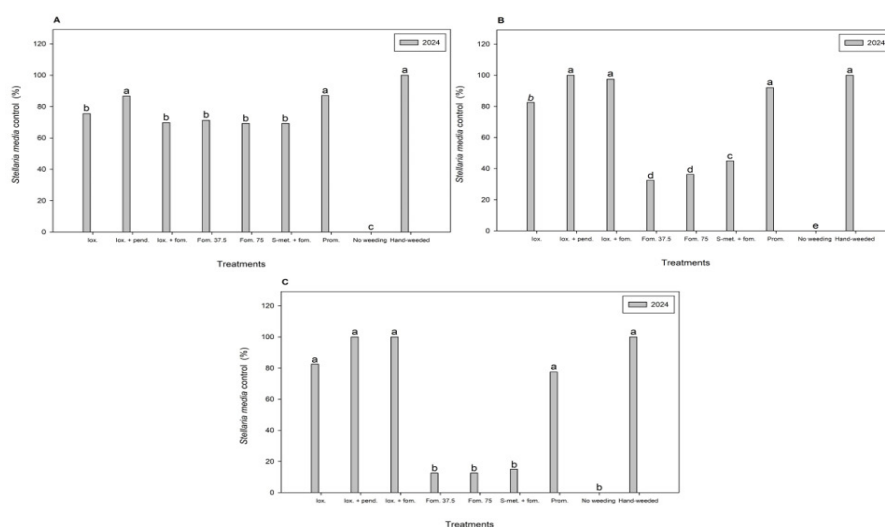
Satisfactory control of *Stellaria media* was obtained only with ioxynil applied alone or in mixtures with pendimethalin or pyroxasulfone. Treatments containing fomesafen (alone or combined with S-metolachlor) provided < 20% control (Figure 4C), highlighting the difficulty of controlling this species with these active ingredients. Among the weed species present, *S. media* was the most challenging, with complete (100%) control achieved exclusively when applied ioxynil + pendimethalin or ioxynil + pyroxasulfone.

Overall, phytotoxicity levels in garlic plants remained low across treatments (Figure 5). Nevertheless,

clear differences were observed among the tested herbicides. Ioxynil alone or mixed with pendimethalin resulted in the lowest phytotoxicity scores in both growing seasons after the three applications.

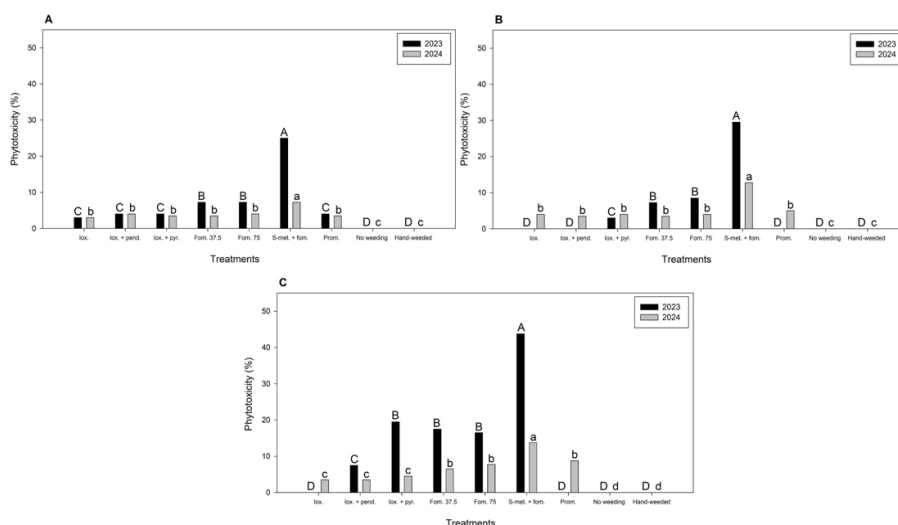
In contrast, the fomesafen + S-metolachlor mixture caused the most severe injury to garlic plants (Figure 5C).

Bulb yield differed significantly among treatments (Figure 6). The highest yields were obtained with ioxynil applied alone and mixed with pendimethalin or pyroxasulfone; these treatments did not differ significantly from the hand-weeded control and exceeded 10,000 kg ha⁻¹ in both growing seasons.



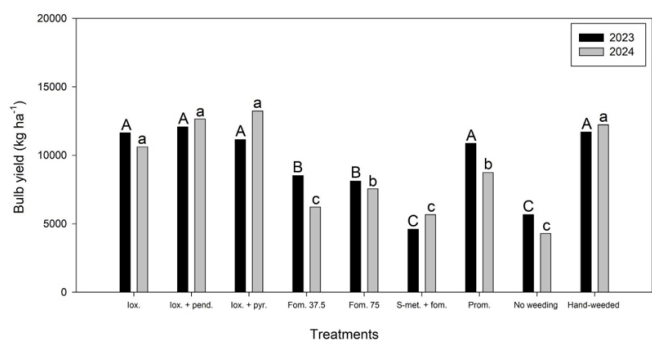
Bars followed by the same letter do not differ significantly according to the Scott-Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom.), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 4. Percentage control (%) of *Stellaria media* 15 days after the first (A), second (B), and third (C) post-emergence herbicide applications in garlic crops during the 2024 growing season, Curitiba, SC, Brazil.



Uppercase letters indicate the 2023 season, and lowercase letters indicate the 2024 season. Bars followed by the same uppercase or lowercase letter do not differ significantly according to the Scott-Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom.), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 5. Phytotoxicity (%) in garlic plants 15 days after the first (A), second (B), and third (C) post-emergence herbicide applications during the 2023 and 2024 growing seasons, Curitiba, SC, Brazil.



Uppercase letters indicate the 2023 season, and lowercase letters indicate the 2024 season. Bars followed by the same uppercase or lowercase letter do not differ significantly according to the Scott-Knott test at the 5% probability level. Treatments: ioxynil 75 g ha⁻¹ (iox), ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹ (iox + pend.), ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 g ha⁻¹ (Fom. 37.5), fomesafen 75 g ha⁻¹ (Fom. 75), S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹ (S-met + fom.), prometryn 250 g ha⁻¹ (Prom.), non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 6. Bulb yield (kg ha⁻¹) of garlic as influenced by post-emergence herbicide applications during the 2023 and 2024 growing seasons, Curitiba, SC, Brazil.

The largest yield reductions in 2023, relative to the hand-weeded control, occurred with fomesafen at 37.5 g ha⁻¹ (27.17%) and 75 g ha⁻¹ (27.80%), with the S-metolachlor + fomesafen mixture (60.70%). In 2024, yield losses were 49.15% and 40.69% for fomesafen at 37.5 and 75 g ha⁻¹, respectively, 53.75% for S-metolachlor + fomesafen, and 28.40% for prometryn.

Bulb size distribution (**Figure 7**) followed the same pattern observed for total yield. In 2023, the highest proportions of large-diameter bulbs (classes 5–7) were obtained with ioxynil applied alone (24.8% in class 5, 7.7% in class 6, and 4.48% in class 7), ioxynil + pendimethalin (40% in class 5, 13.1% in class 6, and 2.3% in class 7), and ioxynil + pyroxasulfone (31.2% in class 5 and 17.8% in class 6). These treatments most closely resembled the hand-weeded control.

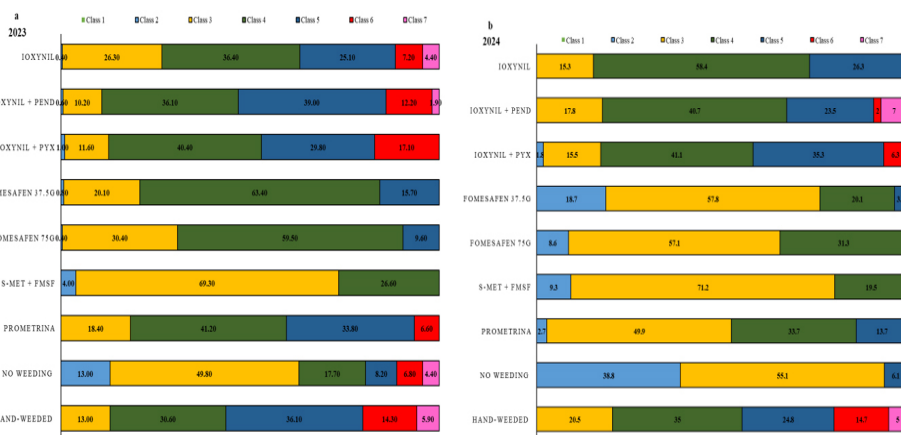
In 2024, ioxynil-based treatments consistently resulted in the highest proportions of commercially

superior bulbs: ioxynil alone (15.3% in class 3, 58.4% in class 4, and 26.3% in class 5), ioxynil + pendimethalin (17.8% in class 3, 49.7% in class 4, 23.5% in class 5, 2% in class 6, and 7% in class 7), and ioxynil + pyroxasulfone (1.8% in class 2, 15.5% in class 3, 41.1% in class 4, 35.3% in class 5, and 6.3% in class 6). In contrast, fomesafen (37.5 and 75 g ha⁻¹), S-metolachlor + fomesafen, and prometryn resulted in the highest proportions of bulbs within the lower commercial classes.

ioxynil is currently the most widely used post-emergence herbicide for broadleaf weed control in garlic cultivation. However, when applied alone during the 2023 growing season, it did not rank among the most effective treatments for controlling *Raphanus raphanistrum*. This reduced efficacy may be attributed to the high vigor and strong competitive ability of this species, which is known to cause substantial yield losses in garlic crops (Lucini, 2009). Similarly, Franceschetti et al. (2019) reported high aggressiveness of *Lolium* spp.—and particularly *Raphanus* sp.—in onion crops, with marked reductions in leaf area, plant height, bulb diameter, and total dry matter.

Mixing ioxynil with the pre-emergence herbicides pyroxasulfone or pendimethalin markedly improved *R. raphanistrum* control in both growing seasons and resulted in a substantially higher percentage of large-diameter bulbs (51–60 mm in classes 6 and 7). This result can be attributed to complementary residual soil activity of pyroxasulfone and pendimethalin, which suppressed early-emerging flushes of *R. raphanistrum* that would otherwise escape post-emergence applications, thereby reducing competition during the early stages of garlic development.

Bulb yield in the ioxynil + pendimethalin and ioxynil + pyroxasulfone treatments did not differ significantly



Treatments: ioxynil 75 g ha⁻¹, ioxynil 75 g ha⁻¹ + pendimethalin 1,820 g ha⁻¹, ioxynil 75 g ha⁻¹ + pyroxasulfone 100 g ha⁻¹ (iox + pyr.), fomesafen 37.5 and 75 g ha⁻¹, S-metolachlor 258.9 g ha⁻¹ + fomesafen 56.9 g ha⁻¹, prometryn 250 g ha⁻¹, non-weeded control (no weeding), and hand-weeded control (hand-weeded).

Figure 7. Commercial classification of garlic bulbs (%) by transverse diameter classes after three post-emergence herbicide applications during the 2023 (A) and 2024 (B) growing seasons, Curitiba, SC, Brazil.

from that of the hand-weeded control in both growing seasons. These findings are consistent with Hajebi et al. (2015), who reported that pendimethalin increased garlic bulb yield by up to 2.4-fold compared with the non-weeded control. Similarly, Bordignon et al. (2024; 2025) demonstrated that pyroxasulfone is highly selective when applied pre-emergence in garlic and post-transplant in onion crops, results that corroborate the present study and indicate the suitability of this active ingredient for both pre- and post-emergence applications in garlic crops.

In 2024, the experimental area exhibited greater weed species diversity, including *Stellaria media*, *Coronopus didymus*, and *Rumex obtusifolius*, in addition to *R. raphanistrum*. Under these infestation conditions, fomesafen-based treatments (alone or in mixture) provided excellent control of *R. raphanistrum* and *C. didymus* but were ineffective against *S. media* (< 20% control) and only moderately effective against *R. obtusifolius*.

S. media is difficult to control due to its low primary dormancy and high germination rate across wide ranges of temperature and moisture conditions, enabling continuous emergence throughout the crop cycle (Grundy et al., 2000; Lucini, 2009). These characteristics contribute to the competitive ability of the species and may explain the ineffective control (< 20%) of fomesafen-based treatments observed in the present study.

Similarly, fomesafen provided only moderate control of *R. obtusifolius*. This perennial species has a deep taproot system with high capacity for dry matter accumulation, which enables rapid regrowth after herbicide applications (Jochem et al., 2020). Furthermore, Trezzi et al. (2009) reported that fomesafen has limited phloem mobility after post-emergence application. This characteristic likely restricted translocation of the active ingredient to the root system of *R. obtusifolius* in the present study, thereby not inhibiting regrowth and resulting in only moderate control efficacy.

The S-metolachlor + fomesafen treatment exhibited significantly lower efficacy against *R. raphanistrum*, *S. media*, and *C. didymus* than the other herbicide treatments. The reduced control obtained with this mixture in 2024 can be attributed to factors intrinsic to the weeds and to the combination of a pre-emergence herbicide (S-metolachlor) with a post-emergence herbicide (fomesafen). The 2024 experimental site had higher clay and organic matter contents than the 2023 site. According to Glaspie et al. (2021), soils higher in clay and organic matter have greater herbicide sorption

capacity, which reduces herbicide concentration in the soil solution and therefore decreases availability for pre-emergence activity. This indicates that soil characteristics influence weed control. These factors collectively explain the lower weed-control efficacy of the S-metolachlor + fomesafen treatment in 2024 and contributed to the high phytotoxicity observed in garlic plants, thereby reducing yield components.

Prometryn provided effective control of the target weed species while causing low phytotoxicity to garlic. Thus, prometryn—along with the ioxynil + pendimethalin and ioxynil + pyroxasulfone mixtures—represents a viable option for post-emergence broadleaf weed management in garlic.

None of the tested herbicides significantly affected garlic plant height or final stand in either growing season. However, the treatments with the lowest weed-control efficacy consistently resulted in the highest levels of phytotoxicity in garlic plants.

Herbicide-induced phytotoxicity in garlic reduces bulb diameter by diverting assimilates that would otherwise support bulb development toward damage repair and stress recovery. This physiological response helps explain the bulb yield and commercial classification data (Figure 7), in which treatments such as S-metolachlor + fomesafen produced the highest proportions of bulbs in lower commercial classes (< 50 mm in classes 2, 3, 4, and 5) and markedly reduced total yield due to the combined effects of ineffective weed control and severe crop injury.

In 2023, the hand-weeded control achieved a mean bulb yield of 11,696.50 kg ha⁻¹ (Figure 6). In contrast, fomesafen applied alone (37.5 and 75 g ha⁻¹), S-metolachlor + fomesafen, and prometryn yielded 8,518.56, 8,444.87, 4,596.72, and 10,864.88 kg ha⁻¹, respectively. In 2024, the hand-weeded control yielded 12,227.57 kg ha⁻¹, whereas the same herbicide treatments significantly reduced yields to 6,217.72 kg ha⁻¹ (fomesafen at 37.5 g ha⁻¹), 7,252.17 kg ha⁻¹ (fomesafen at 75 g ha⁻¹), 5,655.25 kg ha⁻¹ (S-metolachlor + fomesafen), and 8,754.94 kg ha⁻¹ (prometryn).

In 2024, fomesafen at 75 g ha⁻¹ and prometryn reduced mean bulb yield by 4,975 kg ha⁻¹ (40.69%) and 3,473 kg ha⁻¹ (28.40%), respectively, relative to the hand-weeded control. The greatest yield losses occurred with fomesafen at 37.5 g ha⁻¹ (49.15%) and with S-metolachlor + fomesafen (53.75%), both produced yields statistically similar to the non-weeded control.

In summary, mixing ioxynil with pre-emergence herbicides such as pendimethalin or pyroxasulfone

proved to be an effective option for post-emergence herbicide applications in garlic. These combinations integrate distinct modes of action and absorption characteristics, resulting in significantly improved control of the main weed species without affecting bulb quality and yield, thereby demonstrating high selectivity to the crop.

Conclusion

The application of fomesafen alone (37.5 and 75 g ha⁻¹), the S-metolachlor + fomesafen mixture, and prometryn resulted in lower weed-control efficacy and low selectivity to garlic. Consequently, these treatments caused higher levels of phytotoxicity, reducing bulb diameter and total yield.

In contrast, mixtures of ioxynil with pendimethalin or pyroxasulfone effectively controlled *Raphanus raphanistrum*, *Coronopus didymus*, *Stellaria media*, and *Rumex obtusifolius* while exhibiting full selectivity to garlic. These combinations, therefore, represent promising alternatives to the single post-emergence application of ioxynil for broadleaf weed control, ensuring crop safety without reducing bulb quality or yield.

Acknowledgments

The authors thank the Fundação de Amparo à Pesquisa e Inovação do Estado de Santa Catarina (FAPESC) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for funding and institutional support; and the Associação Nacional dos Produtores de Alho (ANAPA) for financial assistance and collaboration. We also thank farmer Everson Tagliari for providing the experimental areas and the necessary inputs.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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