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Impact of Pre-Emergent Herbicides and Soil Management on Weed Community Dynamics and Soybean Yield

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ABSTRACT

Pre-emergent herbicides are key tools in managing herbicide-resistant and hard-to-control weed species in soybean (*Glycine max* L.) cultivation. This study aimed to evaluate the effects of pre-emergent herbicides on weed phytosociology, soybean phytotoxicity, and grain yield under different soil management systems and environmental conditions. Four field experiments were conducted in Brazil (Santo Ângelo and Santa Maria) using a randomized block design across two growing seasons and tillage systems (no-till and conventional). Herbicide treatments included single and combined active ingredients, applied in the plant-and-apply modality. Weed surveys were conducted at 25 and 40 days after emergence (DAE) to calculate the relative importance value index (IVIR), diversity (Simpson and Shannon–Wiener), and similarity indices. Sulfentrazone, trifluralin, and s-metolachlor caused significant phytotoxicity, especially in conventional systems. Herbicide efficacy varied by species and management system. Pyroxasulfone + flumioxazin, metribuzin, and chlorimuron-ethyl significantly reduced the IVIR of dominant species like *Raphanus raphanistrum* and *Euphorbia heterophylla*. Despite observed phytotoxicity, some herbicide combinations improved yield without compromising crop safety. These results underscore the importance of integrating herbicide selection with soil management to optimize weed control and maintain soybean productivity.

1 | Introduction

Pre-emergent herbicides are essential tools in weed management for agricultural crops. A survey on weed management practices in Brazil revealed that 53% of respondents use pre-emergent herbicides in the soybean (*Glycine max* (L.) Merr.) production system [1]. This figure highlights the potential for broader adoption of this management practice, which is crucial for controlling hard-to-manage weeds and addressing herbicide resistance [2, 3]. It is important to note that any alterations in agroecosystem dynamics can influence phytosociological parameters [4], and the use of residual pre-emergent herbicides has the potential to modify the phytosociological characteristics of arable areas [5].

Phytosociology is an essential tool in weed science, as it includes a range of ecological evaluation methods designed to provide a comprehensive overview of the composition and distribution of plant species within a given plant community [6]. Diversity indices can be used to compare plant dynamics

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under various conditions by analyzing species richness and evenness in a population, while cluster analysis can identify patterns among samples [6].

The ability of a management practice to alter the phytosociology of a given area is crucial for developing integrated weed management strategies. In addition to herbicide use, soil and crop management practices can also influence the phytosociology of an area [7]. For instance, long-term no-tillage systems and the use of cover crops can alter the phytosociological makeup of an area by changing the relative importance index (RII) of weeds and their diversity [8, 9]. Furthermore, soil-disturbing practices also have the potential to modify the phytosociological dynamics of weed species [10]. These soil management practices can impact the selectivity, efficiency, and dynamics of pre-emergent herbicides in the soil.

In rice (*Oryza sativa* L.) cultivation, the pre-emergent herbicides penoxsulam, imazethapyr + imazapic, and imazapyr + imazapic reduced the importance value index (IVI) of species in the *Cyperus* genus, while clomazone reduced the IVI of species from the *Poaceae* family [11]. Notably, all herbicide treatments formed a similar cluster of phytosociological parameters, distinct from the control treatment, highlighting the potential impact of pre-emergent herbicides on weed infestations. In cassava (*Manihot esculenta* Crantz) cultivation, S-metolachlor application reduced the frequency and diversity of weeds compared to untreated areas [12]. In a study on corn (*Zea mays* L.), dissimilarity index analysis formed two clusters of phytosociological parameters: one corresponding to the untreated control and another comprising all herbicide treatments [13]. The authors also emphasized that glyphosate + atrazine and atrazine + tembotrione treatments decreased the IVI of weed species in the area.

Thus, understanding the dynamics of the pre-emergent herbicide use in soybean cultivation and their subsequent effects is vital. Few studies integrate soybean cropping systems and different soil types in the phytosociological analysis of weeds. Understanding how soil management and herbicide applications affect phytosociology is a critical step in optimizing production systems. This knowledge can guide management strategies that minimize phytotoxicity while reducing the prevalence of problematic weed species. Accordingly, the hypothesis of this study posits that pre-emergent herbicides influence phytosociology, with effects varying based on soil management and location. The objective of this study, therefore, was to assess the impact of pre-emergent herbicides on weed phytosociology and phytotoxicity in soybean cultivation, comparing different locations and soil management practices.

2 | Material and Methods

2.1 | Site Description

The study was conducted in two distinct locations: Santo Ângelo (28°16′27.6″S and 54°16′13.9″W) and Santa Maria (29°42′56.7″S and 53°43′13.7″W), Rio Grande do Sul, Brazil, under different field conditions and across two soybean growing seasons. In the municipality of Santo Ângelo, during the 2021–2022 season, the experiments were conducted under two cultivation systems: no-tillage and conventional tillage. For the no-tillage system, a cover crop mix was previously cultivated in the area, consisting of rye (*Secale cereale* L.), forage radish (*Raphanus sativus* L.), annual ryegrass (*Lolium multiflorum* Lam.), and common vetch (*Vicia sativa* L.), with an estimated final dry biomass of 2.7 $t \cdot ha^{-1}$. For the conventional tillage system, soil preparation was performed using a disk plow 15 days before soybean sowing. In Santa Maria, two experiments were also conducted. The first was established during the 2021–2022 season under no-tillage on wheat (*Triticum aestivum* L.) straw, with a dry biomass of 1.3 $t \cdot ha^{-1}$.

The second experiment in Santa Maria was conducted during the 2023–2024 growing season in a no-till system on fallow land in the winter (spontaneous vegetation), with the residual dry mass estimated at approximately 1.0 $t \cdot ha^{-1}$. In Santo Ângelo, the soil was classified as an oxisol, with a pH of 5.7, 2.2% organic matter, and 53% clay content. In Santa Maria, the soil was classified as ultisol with a pH of 4.6, 2.9% organic matter, and 31% clay content during the 2021–2022 growing season, whereas in the 2023–2024 season, the conditions were pH 4.6, 2.2% organic matter, and 24% clay content. The climate was characterized as humid subtropical [14].

2.2 | Experimental Design

The experimental design used was a randomized complete block design with four replications, where the experimental units consisted of plots measuring 3×5 m (15 m^2). In the 2021–2022 growing season, the soybean cultivar used was NA 5909 RR (16 plants m^{-1}) at both locations, with sowing in the first half of December. In Santa Maria, during the 2023–2024 growing season, the chosen cultivar was BMX Vênus CE (16 plants m^{-1}), sown on December 1, both cultivars tolerant to glyphosate. The row spacing was 0.45 m. The treatment factor for all experiments consisted of pre-emergence herbicides, applied using a plant-and-apply system (Table 1). The herbicides used are registered for soybean cultivation, with the prescribed doses being applied, except for pendimethalin, which is not registered and whose dose was based on those used in registered crops. The treatments were applied with a CO_2-pressurized backpack sprayer, equipped with flat fan nozzles of the XR 110015 model, calibrated for a spray volume of 150 $L \cdot ha^{-1}$.

2.3 | Data Collection and Analysis

The variables evaluated were herbicide phytotoxicity to the crop, weed phytosociology, and soybean grain yield. The phytotoxicity of the herbicides to soybeans was assessed at 25 (V4-V5 approximately) and 40 (V7-V8 approximately) days after emergence (DAE) using a percentage scale where zero corresponds to the absence of symptoms, while 100 represents plant death. For the phytosociology, two weed surveys were conducted at 25 and 40 DAE of soybean, using random sampling per experimental unit with a metal frame having an internal area of 0.25 m^2. In each sample, the number of individuals present was counted, and identification at the genus and species levels was carried out. Based on the data obtained, the phytosociological variables were calculated according to the methodology proposed by Mueller-Dombois and Ellenberg [15], as described in the equations below:

TABLE 1 | Pre-emergence herbicides used in the experiments.

Treatment	Commercial name	Brand	Dose (g i.a ha^{-1})	Dose (g or L p.c ha^{-1})
T1 – Untreated check	—	—	—	—
T2 – Pyroxasulfone + flumioxazin	Kyojin®	Iharabrás	120 + 80	0.4
T3 – Diclosulam	Spider® 840 WG	Corteva	35.02	41.7
T4 – Trifluralin	Trifluralin Nortox Gold®	Nortox	2250	5
T5 – Flumioxazin	Flumyzin® 500 SC	Sumitomo	75	0.15
T6 – Sulfentrazone + diuron	Stone®	FMC	240 + 490	1.4
T7 – s-metolachlor	Dual Gold®	Syngenta	1920	2
T8 – Chlorimuron-ethyl	Panzer® 250 WDG	Cropchem	20	80
T9 - Sulfentrazone	Boral 500 SC®	FMC	500	1
T10 – Imazethapyr	Zethapir 106 SL®	Sumitomo	106[1]	1
T11 – Pendimenthalin	Prowl H_2O®	BASF	1820	4
T12 – Imazethapyr + flumioxazin	ZethaMaxx®	Sumitomo	120[1] + 60	0.6
T13 – Metribuzin	Sencor 480®	Bayer	480	1
T14 – s-metolachlor + fomesafen	Eddus®	Syngenta	1035 + 239	2
T15 – s-metolachlor + metribuzin	Dual Gold® + Sencor 480®	Syngenta + Bayer	965 + 297	1.08 + 0.62

[1]Acid equivalent.

1. Relative frequency (RF):

$$\mathrm{RF} = \frac{[(\text{Number of samples with the species}/\text{Total number of samples}) \times 100]}{\text{Total frequency of all species in the treatment}}. \quad (1)$$

2. Relative density (RD):

$$\mathrm{RD} = \frac{\left[\left(\text{Number of plants of the same species in the sample}/0.25\,\mathrm{m}^2\right) \times 100\right]}{\text{Total density of all species in the treatment}}. \quad (2)$$

3. Relative abundance (RA):

$$\mathrm{AR} = \frac{[(\text{Number of plants of the same species in the sample}/\text{Number of samples with the species}) \times 100]}{\text{Total abundance of all species in the treatment}}. \quad (3)$$

4. Relative importance value index (IVIR):

$$\mathrm{IVIR} = \mathrm{RF} + \mathrm{RD} + \mathrm{RA}. \quad (4)$$

The RF determines the distribution of species in the samples; the RD represents the number of plants of each species per unit area; and the RA shows the concentration of species in the area. The IVIR determines the most important species present in the survey.

Based on the data from the phytosociological surveys, the effect of pre-emergence treatment was analyzed at 25 and 40 DAE using the Simpson (D) and Shannon–Wiener (H') diversity indices, which express the biodiversity present in the samples [16]. A dendrogram was constructed to compare the pre-emergence treatments and study locations in both evaluations, using the Morisita–Horn similarity index (SI) [17]. This index considers the number of weed plants of each species to generate the similarity grouping. The method used to generate the dendrogram was hierarchical multivariate cluster analysis

using the unweighted pair method with the arithmetic mean. The unweighted pair group method with arithmetic mean (UPGMA) was also applied in the software Past 4.03 [18]. The critical level for separating groups in the cluster analysis was defined using the arithmetic mean of the similarities in the similarity matrix [17].

After the evaluation at 40 DAE, 1040 g a.e of glyphosate (Crucial, Sumitomo Chemical Latin America) was applied to all treatments using flat fan nozzles of the XR 110015 model, calibrated for a spray volume of 150 $L \cdot ha^{-1}$. At soybean maturity, in the phenological stage R8, grain yield was assessed by harvesting 3 m^2 per plot, and the grain moisture was adjusted to 13%. Due to severe drought, it was not possible to harvest the experiments in Santo Ângelo (Figure 1(a)). When significant differences were found by the F test, the means of the phytotoxicity and grain yield variables were separated by the Scott–Knott test ($p < 0.05$). For statistical analysis, the R software [19] and the Easyanova statistical package [20] were used.

3 | Results

Results showed the appearance of several weed species. It was possible to differentiate the patterns of species emergence between the two locations, soil preparation, and the herbicide treatments used in the experiments. The results will be presented below, separated according to the analyzed variables.

3.1 | Phytotoxicity

For the phytotoxicity (%) variable at 25 and 45 days after soybean emergence (DAE), in the conventional tillage system in Santo Ângelo during the 2021–2022 growing season, two mean groupings were formed (Table 2). At 25 DAE, the grouping of the most phytotoxic herbicides consisted of treatments with sulfentrazone and sulfentrazone + diuron, with approximately 21% phytotoxicity, differing from the second grouping, which showed 5.38% phytotoxicity. At 40 DAE, the most phytotoxic grouping had an average value of 13.50% phytotoxicity, composed of trifluralin, sulfentrazone + diuron, s-metolachlor, sulfentrazone, metribuzin, and s-metolachlor + fomesafen, while the other treatments showed an average of 4.56% phytotoxicity.

For the Santo Ângelo location in the no-till system during the 2021–2022 growing season, two mean groupings were also formed in both evaluations. At 25 DAE, the most phytotoxic grouping, with an average of 13.75%, consisted of trifluralin, sulfentrazone + diuron, sulfentrazone, and s-metolachlor + metribuzin, while the other treatments showed 5.45% phytotoxicity in soybeans. At 40 DAE, the most phytotoxic grouping had an average of 12.20% phytotoxicity and included the treatments with diclosulam, trifluralin, sulfentrazone + diuron, sulfentrazone, and s-metolachlor + metribuzin, while the grouping with lower mean values showed 5.90% phytotoxicity (Table 2).

In the Santa Maria location during the 2021–2022 growing season, two mean phytotoxicity groupings were formed at 25 DAE (Table 2). The most phytotoxic grouping consisted of trifluralin, sulfentrazone + diuron, sulfentrazone, pendimethalin, and s-metolachlor + metribuzin, with an average phytotoxicity of 7.80%, higher than the second grouping, which showed 1.40% phytotoxicity. This second grouping did not differ from the control (without herbicide application) (Table 2). At 40 DAE, there was no difference among treatments, all showing an average phytotoxicity of 1.40% (Table 2).

For the 2023–2024 growing season at 25 DAE, two mean groupings were formed, with the highest phytotoxicity grouping represented by diclosulam, sulfentrazone + diuron, s-metolachlor, and sulfentrazone, which exhibited an average phytotoxicity of 10.27%, while the lower phytotoxicity grouping showed 3.73% (Table 2). At 40 DAE, three mean groupings were formed. The most phytotoxic grouping was composed only of sulfentrazone, which caused 18% phytotoxicity, while the second grouping, which included diclosulam, showed 8.75% phytotoxicity (Table 2). The third grouping did not differ from the control and consisted of the other pre-emergence treatments, which showed an average phytotoxicity of 0.50% (Table 2).

3.2 | Phytosociological Indices

For the conventional cropping system in Santo Ângelo, the families with the highest participation were *Brassicaceae*, *Convolvulaceae*, and *Malvaceae* at 25 and 40 DAE. The species *Digitaria ciliaris*, *Ipomoea* spp., *Raphanus raphanistrum*, and *Sida rhombifolia* were observed at 25 DAE (Figure 2(a)). At 40 DAE, in addition to the species mentioned earlier, *Bidens pilosa* and *Richardia brasiliensis* appeared (Figure 2(b)). *R. raphanistrum* had the lowest IVIR in the treatment of s-metolachlor + fomesafen at 25 DAE (Figure 2(a)), while at 40 DAE, it was not present in the treatments with pyroxasulfone + flumioxazin, chlorimuron-ethyl, imazethapyr + flumioxazin, metribuzin, s-metolachlor + fomesafen, and s-metolachlor + metribuzin. For *Ipomoea* spp., at 25 DAE, it was absent in the treatment with sulfentrazone + diuron, and the lowest IVIR were observed in the treatments with diclosulam, s-metolachlor, and sulfentrazone (Figure 2(a)). At 40 DAE, the lowest IVIR for this weed were in the treatments with diclosulam, sulfentrazone + diuron, and s-metolachlor, with no presence observed in the sulfentrazone treatment, while in the applications with s-metolachlor + metribuzin, s-metolachlor + fomesafen, metribuzin, and flumioxazin, the highest IVIR for *Ipomoea* spp. were recorded (Figure 2(b)).

For the no-tillage system in Santo Ângelo, at 25 DAE, the families with the highest participation were *Brassicaceae* and *Poaceae*, and at 40 DAE, the most representative families were *Asteraceae*, *Brassicaceae*, and *Commelinaceae*. At 25 DAE, the species *Conyza* spp., *D. ciliaris*, *Ipomoea* spp., *R. raphanistrum*, *Secale cereale*, and *S. rhombifolia* appeared (Figure 3(a)). At 40 DAE, in addition to the previously mentioned species, *Commelina benghalensis* and *R. brasiliensis* were also observed (Figure 3(b)). At 25 DAE, no weed emergence was recorded in the treatment with chlorimuron-ethyl, and the weeds with the highest IVIR in most treatments were *R. raphanistrum* and *S. cereale* (Figure 3(a)). No presence of *R. raphanistrum* was observed in the treatments with pyroxasulfone + flumioxazin, diclosulam, flumioxazin, imazethapyr, imazethapyr + flumioxazin, and s-metolachlor + metribuzin. In a study conducted under a condition of 11 $t\,ha^{-1}$ of *Panicum maximum* mulch, the herbicides pyroxasulfone + flumioxazin and imazethapyr + diclosulam were effective in controlling dicotyledonous weeds, while for monocotyledons, s-metolachlor + fomesafen, s-metolachlor + imazethapyr, and s-metolachlor + diclosulam were observed to be effective.

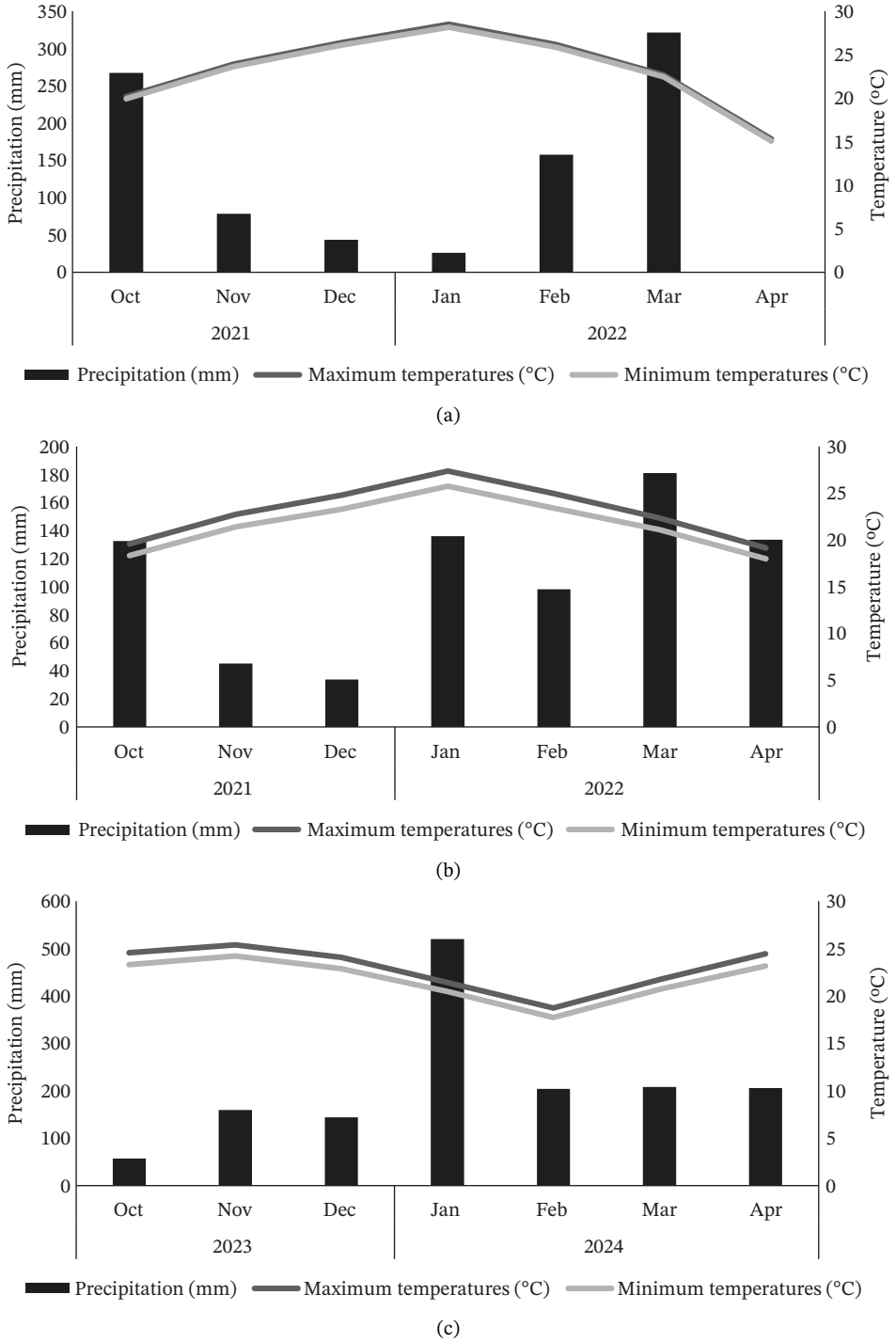


FIGURE 1 | Maximum and minimum temperatures (°C) and precipitation (mm) for Santo Ângelo (a) and Santa Maria (b) in 2021–2022 and for Santa Maria (c) in 2023–2024.

At 40 DAE in the no-tillage system in Santo Ângelo, *Conyza* spp. appeared, with the highest IVIR in the treatments with sulfentrazone and s-metolachlor + fomesafen, while in the treatments with flumioxazin and metribuzin, this plant was not observed (Figure 3(b)). In Santa Maria, in the 2021–2022 crop year, a greater number of species was observed, with *Poaceae* and *Malvaceae* being the most abundant families at both 25 and 40 DAE. At 25 DAE, the species with the highest IVIR in all treatments, except for sulfentrazone, was an unidentified *Poaceae* (Figure 4(a)). No *Conyza* spp. plants were observed in the treatments with sulfentrazone + diuron, imazethapyr + flumioxazin, metribuzin, and s-metolachlor + fomesafen. For *Euphorbia heterophylla*, several treatments were effective, including flumioxazin, sulfentrazone + diuron, sulfentrazone, and metribuzin, with no emergence of this weed. Similarly, the herbicides chlorimuron-ethyl, imazethapyr, pendimethalin, and imazethapyr prevented the emergence of *R. brasiliensis*.

At 40 DAE, for most treatments, the highest IVIR were observed for *Urochloa plantaginea* and *S. rhombifolia* (Figure 4(b)). The

TABLE 2 | Visual evaluation of phytotoxicity (%) of pre-emergence herbicides at 25 and 45 days after emergence (DAE) of soybean in Santo Ângelo under conventional and no-till systems after cover crops and in Santa Maria under no-till system after wheat cultivation, 2021–2022 season, and after fallow, 2023–2024 season.

Treatment	Santo Ângelo				Santa Maria			
	Conventional tillage		No-till system		2021–2022		2023–2024	
	25 DAE	40 DAE	25 DAE	40 DAE	25 DAE	40 DAE	25 DAE	40 DAE
Testemunha sem aplicação	0.00b[1]	0.00b	0.00b	0.00b	0.00b	0.00[ns]	0.00b	0.00c
Pyroxasulfone + flumioxazin	10.00b	8.00b	4.00b	7.00b	0.00b	7.00	3.75b	1.25c
Diclosulam	9.00b	5.00b	8.00b	10.00a	2.00b	7.00	11.25a	8.75b
Trifluralin	9.00b	9.00a	12.00a	12.00a	9.00a	7.00	3.25b	0.00c
Flumioxazin	6.00b	6.00b	4.00b	7.00b	1.00b	0.00	3.75b	0.00c
Sulfentrazone + diuron	23.00a	19.00a	14.00a	14.00a	5.00a	10.00	9.00a	3.76c
S-metolachlor	5.00b	15.00a	6.00b	7.00b	0.00b	9.00	8.33a	0.00c
Chlorimuron-ethyl	4.00b	6.00b	6.00b	7.00b	0.00b	5.00	5.00b	0.00c
Sulfentrazone	19.00a	15.00a	17.00a	14.00a	12.00a	14.00	12.50a	18.00a
Imazethapyr	4.00b	6.00b	8.00b	7.00b	3.00b	8.00	4.75b	0.75c
Pendimenthalin	4.00b	4.00b	7.00b	7.00b	7.00a	4.00	5.00b	1.25c
Imazethapyr + flumioxazin	3.00b	2.00b	5.00b	5.00b	2.00b	4.00	5.00b	0.00c
Metribuzin	3.00b	14.00a	5.00b	5.00b	3.00b	7.00	1.25b	0.00c
S-metolachlor + fomesafen	9.00b	9.00a	7.00b	7.00b	3.00b	9.00	4.50b	1.24c
S-metolachlor + metribuzin	4.00b	4.00b	12.00a	11.00a	6.00a	8.00	4.75b	1.24c
CV (%)[2]	9.44	14.51	7.16	7.8	12.42	14.9	85.39	212.26

Note: [ns]Means did not show significant differences according to the Scott–Knott test ($p \leq 0.05$).
[1]Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).
[2]Coefficient of variation (%).

treatment with trifluralin showed the lowest IVIR for *U. plantaginea*, with no presence of the weed in the treatments with sulfentrazone and sulfentrazone + diuron. *S. rhombifolia* was observed in all treatments, but with the lowest IVIR in the treatment with s-metolachlor + metribuzin. No *Conyza* spp. plants were observed in the treatments with sulfentrazone + diuron and s-metolachlor + metribuzin, with low IVIR in the treatments with metribuzin and s-metolachlor + fomesafen. For *E. heterophylla* and *R. brasiliensis*, at 40 DAE, most pre-emergence herbicides were effective in reducing IVIR.

In Santa Maria, in the 2023–2024 crop year, at 25 DAE, the most prominent family was *Euphorbiaceae*, with the weed species representing this family having the highest IVIR being *E. heterophylla*, which was absent only in the untreated control (Figure 5(a)). The treatment with the lowest IVIR for this weed was sulfentrazone, followed by flumioxazin. With the use of pyroxasulfone + flumioxazin, diclosulam, pendimethalin, imazethapyr + flumioxazin, and s-metolachlor + metribuzin, no presence of *R. brasiliensis* was observed. Similarly, *Ipomoea* spp. was not observed with the use of diclosulam and sulfentrazone, although low IVIR were recorded for all treatments.

At 40 DAE, the main families were *Euphorbiaceae* and *Poaceae*, with the highest IVIR in the treatments divided between *Schizachyrium microstachyum* and *E. heterophylla* (Figure 5(b)). *Schizachyrium microstachyum* emergence was suppressed in the treatments with trifluralin, s-metolachlor, and s-metolachlor + fomesafen, with the lowest IVIR in the treatments with s-metolachlor + metribuzin, metribuzin, imazethapyr + flumioxazin, and pendimethalin. As observed in the first evaluation, *E. heterophylla* was absent in the control treatment, with the lowest IVIR observed with sulfentrazone, flumioxazin, and sulfentrazone + diuron. *Richardia brasiliensis* was not observed with the use of pyroxasulfone + flumioxazin, diclosulam, confirming the results observed at 25 DAE, and s-metolachlor + fomesafen. For *Ipomoea* spp., the results were also similar to those at 25 DAE.

In Santo Ângelo, under conventional soybean cropping system conditions, 25 DAE, the highest Simpson's index (D) was observed with the use of chlorimuron-ethyl and pendimenthalin herbicides (Table 3). For the Shannon–Wiener index (H'), the highest values were recorded for pyroxasulfone + flumioxazin. At 40 DAE, the highest values of index D were observed for diclosulam, the untreated control, imazethapyr, and pendimenthalin, while the treatments with the highest diversity for index H' were diclosulam, imazethapyr, and pendimenthalin (Table 3). In Santo Ângelo, under no-till conditions at 25 DAE, the highest index D was recorded with chlorimuron-ethyl, as no weeds were present, resulting in a null diversity index. This was followed by the s-metolachlor + fomesafen treatment, which also exhibited the highest diversity index H' (Table 3). At 40 DAE, the highest index D was observed with diclosulam, the untreated control, and trifluralin, as well as the highest H' index.

In Santa Maria, under similar cultivation conditions in the 2021–2022 season, the highest diversity for indices D and H' was observed at 25 DAE in treatments with trifluralin, s-metolachlor + fomesafen, s-metolachlor + metribuzin,

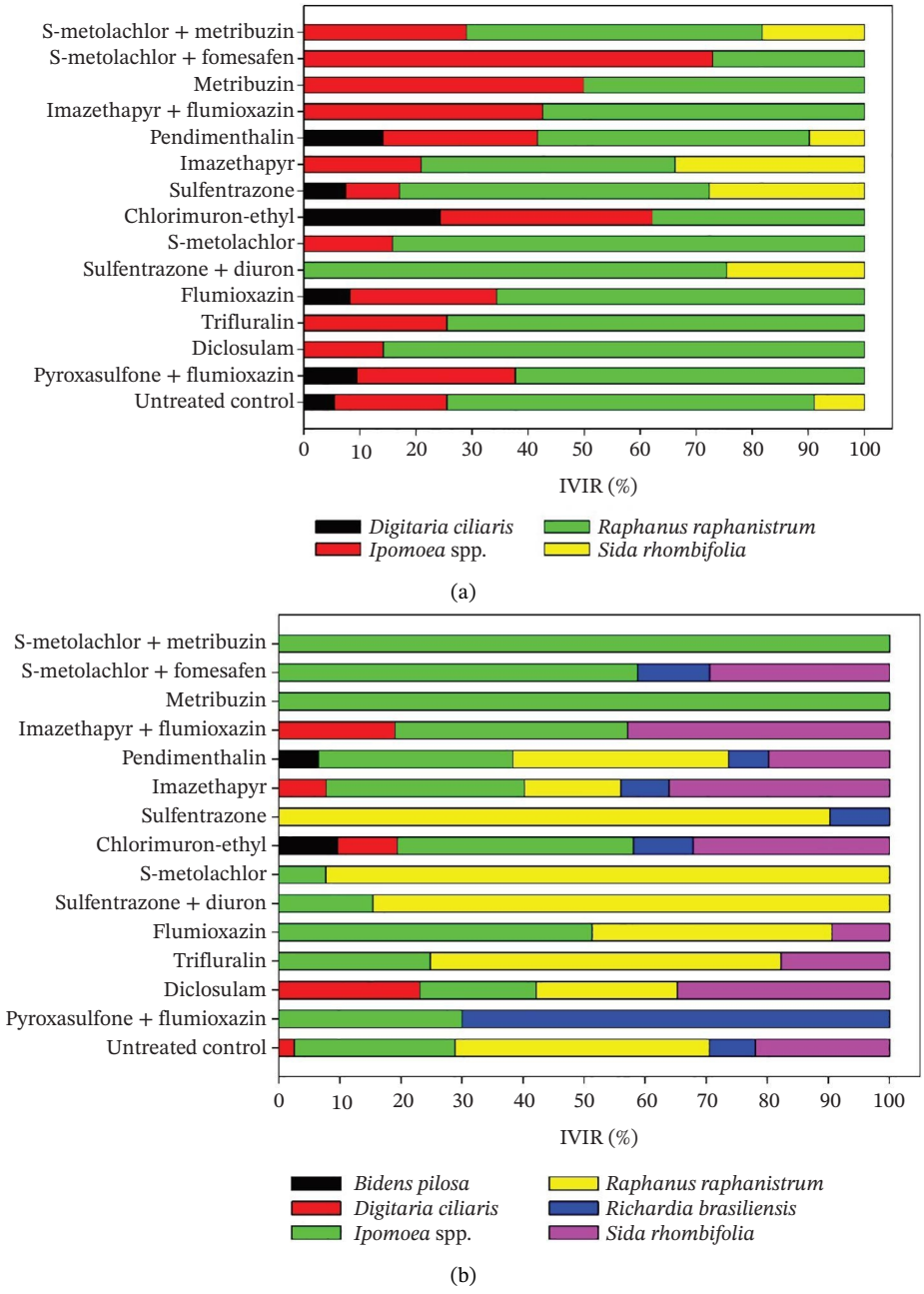


FIGURE 2 | Phytosociological analysis of weed species using the relative importance value index (IVIR) at 25 (a) and 40 days after emergence (DAE) of soybean (b) under conventional tillage system in Santo Ângelo during the 2021–2022 season.

pendimenthalin, and the untreated control (Table 3). At 40 DAE, the treatments with the highest diversity in indices H' and D were flumioxazin, pyroxasulfone + flumioxazin, chlorimuron-ethyl, and s-metolachlor + metribuzin. In Santa Maria during the 2023–2024 season, the highest diversity in indices H' and D at 25 DAE was observed for treatments with flumioxazin, the untreated control, and sulfentrazone + diuron (Table 3). At 40 DAE, the highest diversity for index D was obtained from chlorimuron-ethyl, the untreated control, and diclosulam. These same treatments also exhibited the highest H' indices, alongside treatments with pyroxasulfone + flumioxazin and trifluralin. The dynamics of weed occurrence, as well as their frequency, density, and abundance, varied according to the location, season, and soil management. The SI was obtained through the dendrogram, also known as cluster analysis (Figure 6). The SI ranges from 0 (zero), where there is no similarity between the weed species, to the highest value (1.0), which represents high similarity between the weed species present in the treatments at each location.

For the SI evaluation at 25 days after sowing (DAS), the critical level for the separation of groups occurred at an SI of 0.26 (Figure 6(a)). Consequently, five clusters were formed, which, in general, separated the dendrogram by locations, indicating high floristic similarity within each repetition of the study and low floristic similarity between the studied locations. The treatment with chlorimuron-ethyl in Santo Ângelo under conventional system (T8 SA TILL) formed an isolated group. Thirteen

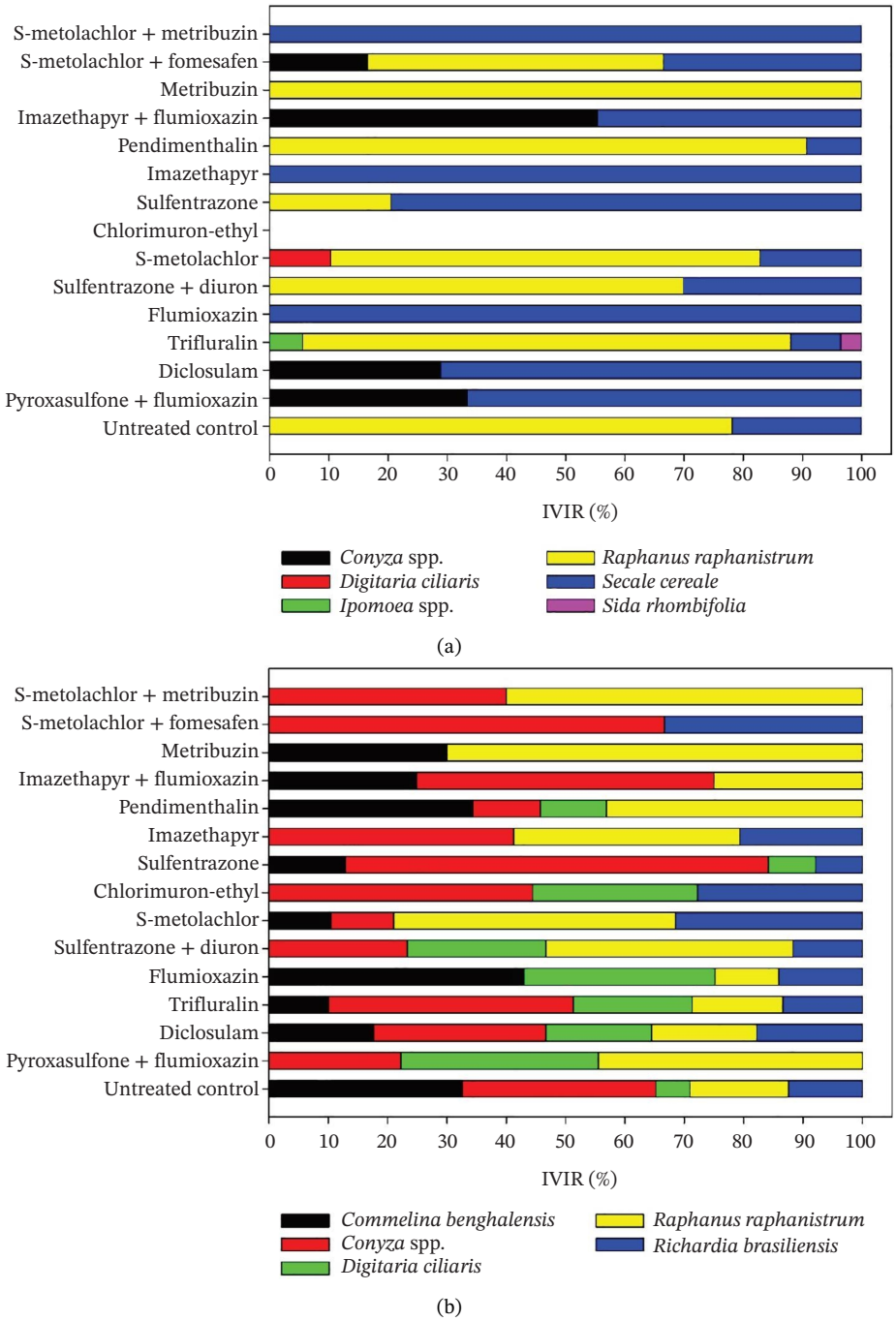


FIGURE 3 | Phytosociological analysis of weed species using the relative importance value index (IVIR) at 25 (a) and 40 days after emergence (DAE) of soybean (b) under no-till system in Santo Ângelo during the 2021–2022 season.

treatments from Santa Maria in the 2023–2024 season (SM 23-24) formed the second group, along with imazethapyr and s-metolachlor + metribuzin from Santa Maria in the 2021–2022 season (T10 and T15 SM 21-22), except for the untreated control and flumioxazin from the 2023–2024 season (T1 and T5 SM 23-24), which predominantly formed the third group, also including 13 treatments from Santa Maria in the 2021–2022 season (SM 21-22). Finally, the treatments from SA TILL and SA NO-TILL formed the third and fourth groups, respectively, which were not as clearly defined as the others. It is worth noting that the critical separation levels for the groups, with an SI of 0.26 (25 DAS) and SI of 0.24 (40 DAS), represent a low similarity value, but subgroups with higher similarity were present within each cluster.

At the evaluation of SI at 40 DAS, four clusters were formed. However, unlike the first evaluation, the first cluster contained 11 treatments from Santo Ângelo under the conventional tillage system (SA TILL) and all treatments from Santa Maria in the 2021–2022 season (Figure 6(b)). The second cluster grouped all treatments from Santo Ângelo under no-till system (SA NO-TILL) and three treatments from SA TILL. The third cluster contained only the treatment from Santo Ângelo with

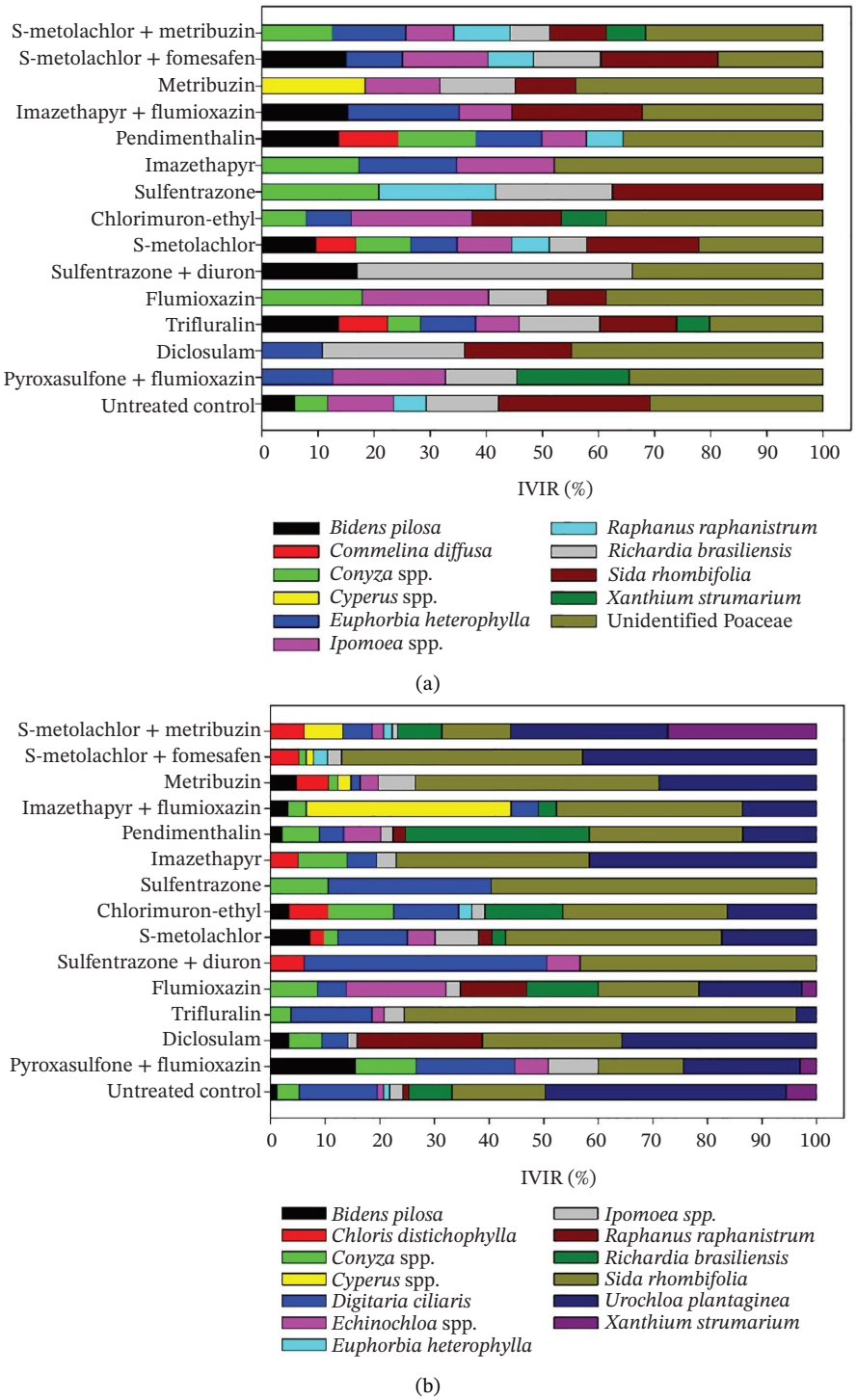


FIGURE 4 | Phytosociological analysis of weed species using the relative importance value index (IVIR) at 25 (a) and 40 days after emergence (DAE) of soybean (b) under no-till system in Santa Maria during the 2021–2022 season.

pyroxasulfone + flumioxazin under the conventional tillage system (SA TILL). The fourth cluster included all treatments from Santa Maria in the 2023–2024 season. The response obtained in the first cluster at 40 DAS (Figure 6(b)) may reflect the soil management employed in the area. For example, in Santo Ângelo, pre-emergence herbicides were applied under a conventional soil preparation system, exposing the soil and leaving no residue (SA TILL), unlike the other three situations, where herbicides were applied to the residue (Figure 6(b)). Within this cluster, two subgroups were formed with an SI close to 0.6, separating SA TILL and SM (2021-2022) into distinct groups.

3.3 | Grain Yield (kg·ha^{-1})

For the grain yield variable, in Santa Maria, two average clusters were formed (Table 4). For Santa Maria in the 2021–2022 season, the lower grain yield cluster consisted of the untreated control and pendimenthalin, with an average grain yield of 2152 kg·ha^{-1},

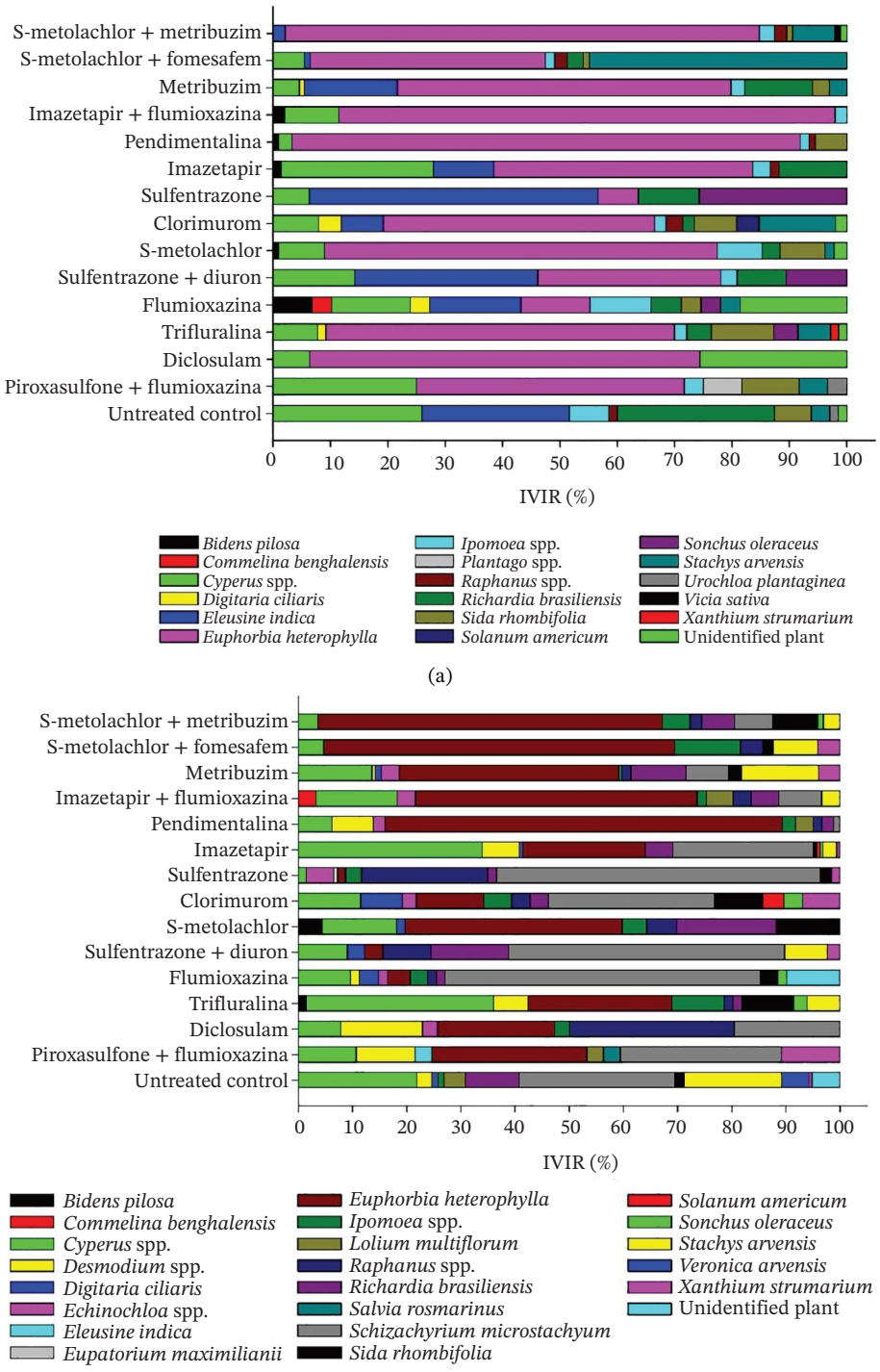


FIGURE 5 | Phytosociological analysis of weed species using the relative importance value index (IVIR) at 25 (a) and 40 days after emergence (DAE) of soybean (b) under no-till system in Santa Maria during the 2023–2024 season.

which was 819 kg·ha^{-1} lower than the other treatments. In the 2023–2024 season, two average clusters were formed. The lower average cluster consisted of the untreated control, diclosulam, trifluralin, flumioxazin, sulfentrazone, pendimenthalin, metribuzin, and s-metolachlor + metribuzin (Table 4), with an average grain yield of 3551 kg·ha^{-1}, representing a loss of 357 kg·ha^{-1} compared to the other treatments. It is noteworthy that the treatment sulfentrazone + diuron was the most phytotoxic in both planting systems at the Santo Ângelo site (Table 2); however, it did not cause any loss of grain yield at the Santa Maria site in both years.

4 | Discussion

4.1 | Phytotoxicity

In general, the sulfentrazone treatment consistently caused the highest phytotoxicity in all environments tested in this study.

TABLE 3 | Weed species diversity by treatment with pre-emergence herbicides using Simpson's (D) and Shannon–Wiener (H') indices at 25 and 40 days after emergence (DAE) of soybean, during the 2021–2022 and 2023–2024 seasons.

Treatment	Santo Ângelo (2021–2022 season)								Santa Maria (2021–2022 season)				Santa Maria (2023–2024 season)			
	Conventional tillage				No-till system											
	25 DAE		40 DAE		25 DAE		40 DAE		25 DAE		40 DAE		25 DAE		40 DAE	
	D	H'	D	H'	D	H'	D	H'	D	H'	D	H'	D	H'	D	H'
Testemunha sem aplicação	0.29	0.84	0.70	1.87	0.29	0.67	0.72	2.02	0.82	2.61	0.70	2.28	0.77	2.38	0.81	2.72
Pyroxasulfone + flumioxazin	0.37	1.94	0.38	1.81	0.44	0.92	0.64	1.53	0.77	2.20	0.83	2.72	0.65	1.97	0.78	2.46
Diclosulam	0.06	0.20	0.74	1.97	0.44	0.92	0.78	2.25	0.72	1.91	0.71	2.11	0.38	0.96	0.80	2.46
Trifluralin	0.18	0.46	0.61	1.47	0.34	1.01	0.70	2.04	0.86	2.97	0.42	1.30	0.58	1.96	0.75	2.46
Flumioxazin	0.32	0.83	0.54	1.23	0.00	0.00	0.67	1.75	0.77	2.20	0.84	2.85	0.87	3.22	0.57	2.04
Sulfentrazone + diuron	0.25	0.60	0.26	0.62	0.38	0.81	0.66	1.76	0.61	1.46	0.57	1.41	0.72	2.11	0.68	2.17
S-metolachlor	0.06	0.20	0.12	0.35	0.46	1.16	0.58	1.55	0.85	2.97	0.74	2.45	0.46	1.52	0.75	2.42
Chlorimuron-ethyl	0.64	1.52	0.67	1.87	1.00	0.00	0.63	1.50	0.78	2.36	0.79	2.58	0.68	2.38	0.83	3.03
Sulfentrazone	0.44	1.15	0.67	1.87	0.28	0.65	0.49	1.35	0.75	2.00	0.52	1.24	0.62	1.77	0.48	1.57
Imazethapyr	0.46	0.94	0.70	1.94	0.00	0.00	0.57	1.38	0.67	1.79	0.66	1.86	0.67	1.92	0.73	2.22
Pendimenthalin	0.58	1.55	0.70	1.93	0.11	0.32	0.64	1.68	0.82	2.62	0.74	2.35	0.17	0.61	0.42	1.46
Imazethapyr + flumioxazin	0.46	0.94	0.61	1.45	0.44	0.92	0.63	1.50	0.72	2.06	0.74	2.35	0.67	1.92	0.67	2.24
Metribuzin	0.50	1.00	0.00	0.00	0.00	0.00	0.38	0.81	0.69	2.00	0.65	1.99	0.57	1.80	0.74	2.48
S-metolachlor + fomesafen	0.28	0.65	0.52	1.24	0.61	1.46	0.44	0.92	0.84	2.70	0.65	1.99	0.61	1.67	0.53	1.68
S-metolachlor + metribuzin	0.53	1.30	0.00	0.00	0.00	0.00	0.48	0.97	0.82	2.75	0.79	2.63	0.23	0.85	0.52	1.77

Another treatment that caused phytotoxicity in the 2021–2022 season was trifluralin. A study evaluated the application of pre-emergence herbicides sulfentrazone + diuron and imazethapyr + flumioxazin at different doses, with or without glyphosate, on the cover crop residue [21]. When comparing the same doses used in our study, the authors observed 7% phytotoxicity for sulfentrazone + diuron and 11% for imazethapyr + flumioxazin at 21 DAE. In a study aimed at the pre-emergence control of *Amaranthus tuberculatus*, it was observed that increasing the active ingredient dose of pyroxasulfone + flumioxazin per hectare increased phytotoxicity in soybeans, but grain yield was similar to the weeding control [22].

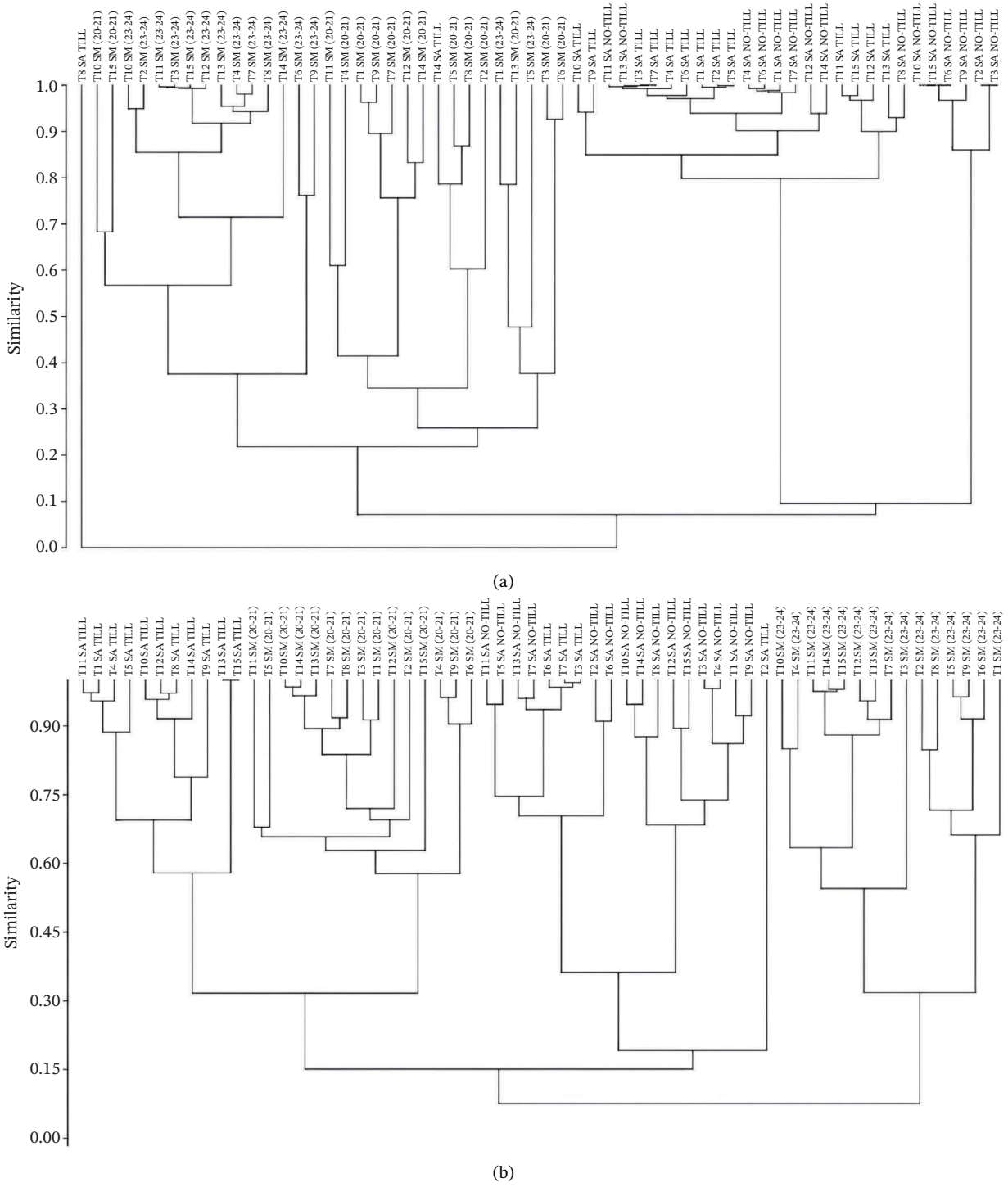
This observation can be explained by the herbicide sulfentrazone, whose sorption in the soil is influenced by the chemical and physical characteristics of the soil. The efficacy of this herbicide is reduced as organic matter content and pH values approach its pKa, indicating a lower amount of herbicide in the soil solution to exert its action [23]. Additionally, sulfentrazone has a low octanol-carbon coefficient (koc), meaning it does not adsorb well onto carbon present in cover crop residues [24]. Similarly, the sorption of the herbicide diuron is proportional to the soil organic matter content, and it is considered less leachable in clayey soils, with moderate leaching in soils with low organic matter and clay content [25]. A correlation was also observed between the soil organic matter and clay content, where higher values resulted in a higher adsorption coefficient for trifluralin [26] and s-metolachlor [27].

When evaluating herbicides pyroxasulfone, s-metolachlor, and trifluralin on different levels of soybean and corn straw, pyroxasulfone was the most effective herbicide on both types of straw, followed by s-metolachlor, while trifluralin showed the greatest reduction in efficacy as the amount of straw increased [28]. The herbicide–straw–phytotoxicity interaction system can be complex. A study testing these conditions found that when the straw was incorporated by sowing after application (apply-plant system), the control of *Amaranthus hybridus* (smooth pigweed) with clomazone, s-metolachlor, and pendimethalin was worse compared to the plant-apply system [29]. Furthermore, herbicide movement in the straw is also influenced by moisture, with herbicides like sulfentrazone and diuron able to move through both dry and wet straw [30]. This movement is important for herbicide efficacy, as contact with the straw can result in sorption and reduced effectiveness [31].

Overall, it is also noteworthy that the highest phytotoxicity of herbicides to soybeans occurred in the conventional tillage system and when the area remained in winter fallow. This observation may be related to the greater exposure of the soil due to the absence of vegetation cover, which could have favored higher herbicide concentration in the soil and greater phytotoxicity in the conventional tillage system and areas previously covered with spontaneous vegetation. In other conditions, the wheat straw in Santa Maria and the cover crop mix in Santo Ângelo may have helped retain the spray, limiting its contact with the soil.

4.2 | Phytosociological Indices

A study evaluating cropping systems and soil preparation for soybean cultivation found that 10 botanical families were identified in the no-tillage system, while only 7 families were found in the conventional system [7]. The same study highlighted that the family *Poaceae* predominated in the conventional cropping system, representing 66% of the species, with *Fabaceae*, *Malvaceae*, and *Euphorbiaceae* also considered important in both systems, though in different proportions. These conditions were



(a)

(b)

FIGURE 6 | Cluster analysis for similarity between weed species observed at different locations (SA – Santo Ângelo; SM – Santa Maria) for treatments with pre-emergence herbicides at 25 days after emergence (DAE) of soybean, cophenetic coefficient of 0.97 (a) and at 40 DAE, cophenetic coefficient of 0.84 (b). The composition of the treatments is provided in Table 1.

similar to those observed in the experiments conducted in Santo Ângelo and corroborate the results found in our study.

A study conducted in rice cultivation observed that the treatments imazethapyr + imazapic and imazapyr + imazapic were effective in reducing the number of plants m^{-2} of *Echinochloa crusgalli*, and the IVIR was reduced to 0% and 8.60%, respectively, compared to the control treatment with 22.60% [11]. On the other hand, *Cyperus esculentus* showed control failures, possibly due to differences in susceptibility. It is worth noting that pre-emergence herbicides altered the phytosociological variables because, most of the time, they are limited to a specific group of weed species related to their control spectrum and also to the susceptibility of the species [32]. Therefore, understanding the phytosociology of weed species is essential as a complementary tool to the visual control analyses commonly performed in research studies.

TABLE 4 | Soybean grain yield (kg·ha^{-1}) in Santa Maria under no-till system after wheat cultivation, 2021–2022 season, and after fallow, 2023–2024 season.

Treatment	Grain yield (kg·ha^{-1})	
	2021-2022	2023-2024
Testemunha sem aplicação	1945.57b[1]	3634.04b
Pyroxasulfone + flumioxazin	2960.57a	4030.58a
Diclosulam	3173.09a	3575.07b
Trifluralin	2635.63a	3430.22b
Flumioxazin	2897.52a	3615.47b
Sulfentrazone + diuron	3391.05a	3861.76a
S-metolachlor	2628.02a	3859.93a
Chlorimuron-ethyl	2816.65a	3797.24a
Sulfentrazone	2945.50a	3613.36b
Imazethapyr	3074.15a	3809.16a
Pendimenthalin	2357.98b	3487.90b
Imazethapyr + flumioxazin	3202.67a	4141.51a
Metribuzin	2888.67a	3522.90b
S-metolachlor + fomesafen	3080.35a	3980.49a
S-metolachlor + metribuzin	2926.08a	3527.07b
CV (%)[2]	16.49	8.43

[1]Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).
[2]Coefficient of variation (%).

A study conducted in rice cultivation with different cropping systems and management practices over three seasons found that the management with pendimenthalin effectively controlled grasses but did not control sedges, leading to population shifts in plots with the pre-emergence herbicide [33]. The authors also noted that the diversity, measured by the Shannon–Wiener index, was higher in the untreated control, indicating greater species diversity, followed by the direct-seeding rice management and the use of the pre-emergence herbicide, which occurred due to the selection of weed species over the study seasons.

In general overview, chlorimuron-ethyl, pendimenthalin, and diclosulam frequently appeared among the herbicides with the highest *D* indices. This suggests that there is a probability that two randomly collected individuals from the same area belong to the same species, indicating that these herbicides selected the population. A study conducted in rice cultivation under sprinkler irrigation observed that the diversity between treatments, as measured by the *D* index, was similar, reducing the number of highly prolific species, except for imazethapyr + imazapic, which caused an imbalance in the occurrence of the prolific species *Fimbristyllis* sp. and *Killinga brevifolia* [11]. Similarly, a study conducted in corn cultivation showed similar values for the *D* index among treatments, except for the atrazine + glyphosate treatment, which exhibited the lowest index [32]. In the same study, the H' index showed similar behavior to the *D* index, with the highest diversity observed in the herbicide-free treatment.

The H' index, in turn, is influenced by rare species. The higher the H' index, the greater the species diversity within the population. An ideal approach would be to achieve high levels of weed control while maintaining a high diversity in the system (Concenço et al., 2013). Thus, considering both control and maintenance of floristic diversity, these treatments proved to be good options.

Overall, climate is also an important factor influencing the emergence of each weed species within an agricultural ecosystem. Each species has a specific base and optimal temperature for germination [34]. This makes the primary difference in the emergence flow of weeds, and subsequently their diversity, dependent on climatic conditions. For example, the germination of species such as *S. rhombifolia* occurs at a base temperature of 10.0° C, whereas for *Ipomoea triloba*, these values are around 12.32°C [35, 36]. It was observed that in the first year of the trial, the temperature was similar at both locations, but the 2023–2024 season exhibited milder temperatures, particularly in January, February, and March, which enhanced the emergence of weeds with lower base temperatures [34]. The application of pre-emergence herbicides under conventional tillage facilitates herbicide contact with the soil, potentially enhancing control and increasing phytotoxicity. In residue-covered situations, the herbicide may adsorb onto the organic matter and fail to make direct contact. For this reason, in residue-covered situations, herbicides should be applied that can move through the residue [30].

4.3 | Grain Yield (kg·ha^{-1})

A study conducted under no-till conditions with winter cover crop residue, in soils with pH 4.8 and 62% clay, observed that treatments with sulfentrazone + diuron and imazethapyr + flumioxazin, at the same doses used in our study, resulted in productivities of 871 and 2676 kg·ha^{-1}, respectively [21]. Another study, conducted under conditions of pH 5.5 and 51% clay, showed no phytotoxicity in soybean cultivation, and in this case, there was no statistical difference in grain yield between the weeding control and treatments with sulfentrazone + diuron [25]. Similarly, the use of higher doses of pyroxasulfone + flumioxazin resulted in productivities close to the untreated control, as the observed loss in grain yield was caused by the interference of *Amaranthus tuberculatus* [22]. In rice (*Oryza sativa* L.) cultivation, producers who reported phytotoxicity caused by pre-emergence herbicides did not experience any average grain yield loss when compared to those who did not report phytotoxicity [32]. In wheat, the soil played a role on herbicidal phytotoxicity; the soil with low clay content showed more injuries than the more clay content one, with this behavior being shown with several herbicides [37].

Furthermore, although some of the treatments tested resulted in soybean grain yield losses, this response could be attributed to the infestation of weeds in the treatment and the competition they imposed on the crop. A study highlighted that pre-emergence treatments with metribuzin, sulfentrazone, metribuzin + alachlor, and alachlor showed high control of weeds in *Vigna unguiculata* but caused grain yield losses exceeding 60% [38]. However, some molecules, such as sulfentrazone, have potential phytotoxicity in soybean [24], primarily when used at doses above 500 g·ha^{-1} [39]. Overall, pyroxasulfone + flumioxazin, chlorimuron-ethyl, imazethapyr + flumioxazin, metribuzin, and s-metolachlor + fomesafen were effective in reducing the IVIR of *Raphanus raphanistrum*. *Euphorbia heterophylla* showed the lowest IVIR when treated with sulfentrazone and flumioxazin. The treatments with

sulfentrazone + diuron, s-metolachlor, imazethapyr + flumioxazin, and s-metolachlor + fomesafen exhibited phytotoxicity but did not negatively affect grain yield.

Author Contributions

Eduarda Grün, Roberto Costa Avila Neto, and André da Rosa Ulguim contributed to the study conception and design, material preparation, data collection, and data analysis. The first draft of the manuscript was written by Eduarda Grün with substantial revisions by Roberto Costa Avila Neto and André da Rosa Ulguim. Arícia Ritter Corrêa, Eduard Mroginski Leichtweis, Eduardo Streck Bortolin, Kayky Victor Volff Reis, Natália Heinzmann, and Pedro Henrique Folharini contributed to data collection, literature review, and preparation of figures and tables. All authors contributed to the interpretation and discussion of results and commented on previous versions of the manuscript.

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Disclosure

All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon request.

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