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RESEARCH

Herbicide Strategies for Weed Control and Soil Seed Bank Dynamics in Winter Wheat

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Abstract
Weed interference, especially during early growth stages, significantly reduces winter wheat (*Triticum aestivum* L.) yield. A three-year field study (2021–2023), conducted in Tokat, Turkey, aimed to determine the effectiveness of pre-sowing glyphosate (PSG) and pre-emergence pyroxasulfone (PEP), in combination with post-emergence tribenuron-methyl (PET) and hand weeding, on weed control, wheat yield, and soil weed seed bank dynamics. Treatments were evaluated in a split-plot design with four replications. PSG + hand weeding resulted in the highest weed control and grain yields, ranging from 5142.3 to 6513.0 kg ha^{-1}, followed closely by hand weeding with 5064.0 to 6286.0 kg ha^{-1} grain yield. In contrast, the yields in untreated weedy control plots were only 3787.5 to 4710.0 kg ha^{-1}. The integration of PSG with PET increased yield by 687–1197 kg ha^{-1} compared to PET only. PEP treatment in 2023 controlled *Amaranthus retroflexus* and *Portulaca oleracea* by ≥90%, while moderately affecting *Chenopodium album, Solanum nigrum*, and other weeds. Moreover, pre-sowing and pre-emergence treatments significantly reduced the density of dominant weed seeds in the soil, especially *A. retroflexus* and *C. album*. These results showed the importance of integrating pre-sowing or pre-emergence herbicides with cultural practices like hand weeding to improve weed suppression, yield performance, and long-term soil seed bank management in winter wheat.

Keywords Glyphosate potassium salt · Pyroxasulfone · Tribenuron-methyl · Weed control · Soil seed bank

Introduction

Wheat's ecological plasticity and storage resilience have facilitated reaching the border of the wide distribution region in both hemispheres (Dalrymple 1986). Turkey ranks among the top tenth wheat-producing countries, with 19 million tons per year (USDA 2025). However, Türkiye remains one of the leading global wheat importers in the world with $ 3.5 billion even if it has a strong domestic production (Workman 2024). Therefore, enhancing wheat yield and quality is a prominent aim of agronomists and plant breeders in Türkiye.

As one of the origin countries of wheat, Turkish wheat fields are burdened many biotic suppressors, including weeds, pests, and phytopathogens (Duveiller et al. 2007; FAO 2015). The weeds can cause up to 34% grain winter wheat yield loss depending on the weeds, region, weather, and cultural practices, due to mainly competition for nutrients, water, and space (Flessner et al. 2021). They are also reservoirs for pests and pathogens in winter wheat, further exacerbating yield losses. Moreover, their seeds contaminate the harvest, and their presence in the harvest reaches up to 13.11% (Tepe 1998). The local weed flora in Türkiye consists of 23 annual and 3 perennial grass weeds and 72 annual and 13 perennial broadleaf weeds (GTHB 2008).

As in other cereal crops, winter wheat is vulnerable to weed competition, especially during its early developmental stages. Therefore, a weed-free environment during this stage can facilitate robust crop establishment and enhance competitiveness against weeds (Serim et al. 2025). Pre-sowing herbicides are effective and affordable choices to

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kill newly emerged seedlings with minimal crop injury (Montgomery et al. 2024), particularly for controlling herbicide-resistant weeds (Neve et al. 2003). For instance, Doğan et al. (2009) indicated that pre-sowing glyphosate treatment, without seedbed preparation, effectively suppressed both annual weeds and perennial weeds such as *Cyperus rotundus* and *Sorghum halepense*. Albrecht et al. (2020) similarly demonstrated that sequential or combined application of glufosinate with some herbicides such as glyphosate, 2,4-D, saflufenacil, saflufenacil/imazethapyr, diclosulam, paraquat/diuron, paraquat and imazethapyr/flumioxazin successfully controlled *Conyza* spp. in soybean when used prior sowing. Sequential applications of herbicide/herbicide combinations before sowing have also shown greater efficacy than single treatments in suppressing *C. sumatrensis* (Retz.) E. H. Walker (Cantu et al. 2021). In another similar study, Shah et al. (2025) showed the sequential application of pre-emergence pendimethalin (1.0 kg ai ha^{-1}) and post-emergence metribuzin (0.2 kg ai ha^{-1}) provided effective grasses and broadleaf weed control. Like pre-sowing herbicides, pre-emergence herbicides are also powerful components of integrated weed management strategies in the crop fields and increase the grain yields of field crops.

Residual pre-emergence herbicides remain in the soil for a long time until crops become more competent against weeds (Kleemann et al. 2016; Oliveira et al. 2017). Although certain herbicides, such as penoxsulam, can be applied both pre-emergence and post-emergence, their efficacy when used pre-emergence is several times greater than post-emergence treatments (Turra et al. 2023). Pre-emergence herbicides may reduce the need for labor-intensive manual or mechanical weeding during the seedling stages of crops. Moreover, these herbicides significantly enhance weed control when followed by post-emergence herbicides compared to single application (Sepat and Singh 2024).

Soil seed bank (SSB) is the main source of weed flora in crop fields and plays a pivotal role in continuing the presence of weed species in a specific field (Feledyn-Szewczyk et al. 2020). Each treatment that has an impact on the SSB significantly changes the weed flora depending on some environmental conditions, including soil moisture and temperature, and agricultural practices such as tillage, and weed control treatments (Chauhan and Johnson 2010; Zamljen and Leskovšek 2024). Therefore, managing SSB meant managing weed arable weeds in the following season. Among them, herbicides, especially residual ones, are real game-changers because of have a long-term impact.

The Integrated Pest Management (IPM) guidelines for Turkish wheat fields primarily focus on the management of annual weeds, even though perennial weeds are mentioned in them (Wheat IPM Guideline 2017). Continuous use of herbicides with the same mode of action has led to the emergence of herbicide resistant weeds, such as winter wild oats, in Turkish wheat fields (Türkseven et al. 2022), and more than half of these weeds were found in Turkish wheat fields (Heap 2025). Another significant challenge faced by Turkish wheat farmers is the control of perennial weeds. Although some studies have investigated their negative impact on grain yield and quality, no practical management strategies have yet been recommended to farmers for effectively addressing these weeds. This study aimed to determine the effectiveness of pre-sowing and pre-emergence herbicide application in an herbicide application program on weed dynamics, wheat grain yield, and the weed seed bank in winter wheat cultivation.

Material and Methods

Field trials were conducted over three consecutive years from 2021 to 2023 at the Middle Black Sea Transaction Zone Agricultural Research Institute (40.1928N; 36.2656E) in Kazova, Tokat, Turkey. The soil consisted of clay loam containing 1.5% organic matter and a pH of 7.9. Two tillage treatments were carried out in September and October. Primary tillage was performed using a rotary tiller, followed by secondary tillage with a combined cultivator. The Flamura-85 winter wheat cultivar was planted at a density of 500 seeds m^{-2} on December 02, 2020; November 09, 2021, and November 19, 2022. This variety is recognized for its resistance to cold and lodging. The site experiences a continental climate with distinct seasonal variation (Fig. 1).

The field was naturally infested with prevalent winter wheat weeds such as *Veronica hederifolia* L., *Chenopodium album* L., *Amaranthus retroflexus* L., *Sinapis arvensis* L., *Galium aparine* L., *Fumaria officinalis* L., *Portulaca oleracea* L., and *Seteria viridis* L.

The study was designed as a split-plot experiment with four replications. Pre-sowing/emergence herbicide (PSH/PEH) treatment and no PSH/PEH were kept in the main plots, and the subplots were allocated to the weed control treatments, including post-emergence herbicide, hand-weeding, and weedy check. Each plot measured 3.0 m × 3.5 m with 18 cm row spacing. They were protected by buffers 2 m-wide between the blocks, and 1 m-wide between the plots. In 2021 and 2022, the treatments were as follows: pre-sowing glyphosate potassium salt (PSG) + Post-emergence tribenuron-methyl (PET), PSG, PET, PSG + hand weeding, hand weeding, and weedy check. In 2023, PSGs were replaced by Pre-emergence pyroxasulfone (PEP). Hand weeding was started on March 15, 2021, March 5, 2022, and March 6, 2023, and repeated 3 times at 10-day intervals after tillering began.

PSH, PEH, and post-emergence herbicide were applied using a field sprayer and motorized backpack sprayer

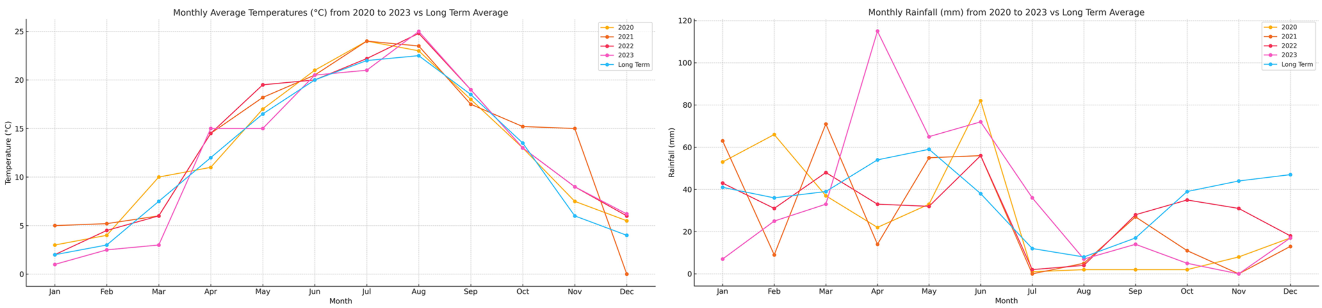

Fig. 1 Monthly average temperatures (left) and rainfall (right) of experimental fields from 2021–23 and long-term (MGM 2024)

adjusted to deliver 200 l ha^{-1} at 200 kPa pressure, respectively. Glyphosate potassium salt (ROUNDUP STAR®; Bayer Crop Science, İstanbul, Türkiye) was applied before sowing on November 11, 2020, and October 25, 2021, while Pyroxasulfone (KELT WG 85®; Bayer Crop Science, İstanbul, Türkiye) was used before emergence on November 29, 2022. Glyphosate potassium salt (Soluble concentrate), pyroxasulfone (Water-dispersible granule), and tribenuron-methyl (GRANSTAR®; FMC Turkey, İstanbul, Türkiye; Water-dispersible granule) were applied at a rate of 2.646 kg ai ha^{-1}, 127.5 g ai ha^{-1}, and 7.5 g ai ha^{-1}, respectively, to control grass and broadleaf weeds.

Weed species were identified at the tillering stage using a 1 m^2 frame and classified according to the Flora of Turkey and the East Aegean Islands (Davis, 1965–1985). Herbicide efficacy was visually evaluated at 21 DAT based on reduction in the weed density and growth, and visible symptoms such as necrosis and chlorosis using a 0–100% scale relative to the untreated control, where 0% indicated no impact of herbicides, while 100% represented complete plant death.

The wheat ears were harvested by hand and brought to the laboratory to thresh and dry. Yield was calculated on a per-hectare basis from measured harvest areas.

Soil Seed Bank Assessment

The impact of all weed control treatments on the weed seed bank was evaluated annually. Soil samples were collected from each plot using a 5 cm-diameter soil borer at 10 cm soil depth. The soil samples were first sieved (4 mm × 4 mm) to remove unwanted materials, then sieved using a precise sieve (0.25 mm × 0.25 mm) to separate soil aggregates. A flotation method was used to separate weed seeds: samples were submerged in water for 24 h, gently agitated, and rinsed over sieves. The seeds were dried using towel papers, put in paper bags, and stored in a cooler at +4 °C until classification. Weed species in the seed bank were identified using the Flora of Turkey and the North Aegean Islands (Davis, 1965–1985).

Statistical Analysis

All data analyses were conducted using the agricolae package (Mendiburu and Yaseen 2020) in R statistical software (RStudio Team 2024). The effects of the PSG/PEP alone or with weed control treatments on wheat yield and weed-related data were analyzed separately for each year due to significant year-by-treatment interaction effects ($P < 0.05$). Analysis of variance (ANOVA) was performed to assess treatment effects, and treatment means were compared using Fisher's Protected Least Significant Difference (LSD) test at the 5% significance level.

Results and Discussion

Weed Control Efficacy

No visible crop injury was observed in response to PSG, PEP, or PET applications. Winter wheat density in pre-herbicide applied plots was similar to that of the density of control plots. Similar to these herbicides, PET caused no significant injury in winter wheat at 21 DAT.

Hand weeding was a powerful tool to control weeds in 2021 and 2022 even if it required intensive labour, and was a time-consuming and expensive treatment. Notably, the combination of PSG and hand weeding enhanced weed control while reducing the labor required compared to hand weeding alone. PET demonstrated ≥ 80% control for most weeds, including *C. album, C. arvense, F. officinalis, S. arvensis, P. oleracea, L. serriola, S. nigrum*, and *A. retroflexus*. However, its efficacy was limited (60–80%) against species, such as *X. strumarium, P. aviculare*, and *C. arvensis* (Fig. 2). Conversely, weeds such as *V. hederifolia, G. aparine, S. viridis*, and *A. myosuroides* were not within the PET's spectrum of activity.

PSG alone statistically had the least weed control effects compared to other treatments. This treatment effectively controlled the autumn-emerging weeds, but had limited effect in spring because glyphosate had no residual effect (Figs. 2 and 3). Therefore, a slight difference was observed

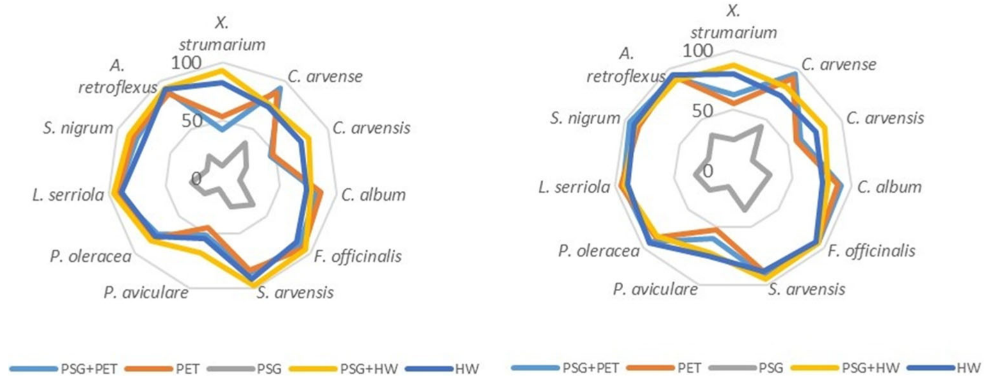

Fig. 2 Response of the weed species to various weed control treatments in 2021 (left) and 2022 (Right) (*PGS* Pre-sowing glyphosate, *PET* Post-emergence tribenuron-methyl; *HW* Hand-weeding)

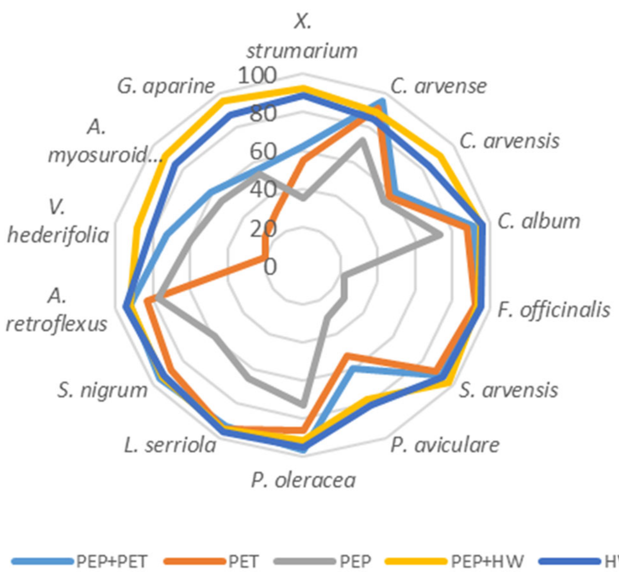

Fig. 3 Response of the weed species to various weed control treatments in 2023 (*PEP* Pre-emergence pyroxasulfone, *PET* Post-emergence tribenuron-methyl; *HW* Hand-weeding)

between PSG + PET and PET alone in 2021, while a noticeable difference was observed in 2022 with increased autumn rainfall (Fig. 2). These results align with Gandía et al. (2021), who indicated the influence of precipitation on weed germination and herbicide efficacy.

PSG + HW was statistically the most effective weed control treatment in the experiment, particularly for controlling *X. stramonium, C. arvensis*, and *P. aviculare* in 2021 ($P<$ 0.05). This finding is consistent with the results reported by Šikuljak Pavlović et al. (2023) who reported that preplanting glyphosate application + mechanical weed control treatments made using a rotary harrowing and a cultivator three times in tomatoes had a similar impact on the weed density with that of mechanical weed control treatments. In 2022, the differences between the treatments become less apparent compared to the previous year. However, all treatments, except PSG, showed a similar effectiveness in controlling weeds such as *A. retroflexus, S. nigrum, L. serriola, P. oleracea, S. arvensis,* and *F. officinalis* ($P>0.05$).

In 2023, PEP effectively controlled ≥ 90% of *A. retroflexus* and *P. oleracea*, and moderately suppressed species such as *C. album, C. arvense, S. nigrum, V. hederifolia*, and *G. aparine* (Fig. 3). PET continued to be effective against most weeds except *V. hederifolia, G. aparine*, and *P. aviculare*. The combined use of PEP + PET enhanced weed control efficacy. These findings are consistent with Shah et al. (2025), who examined how different combinations of pre-emergence and post-emergence herbicides and hand weeding improve the control of weeds in wheat fields compared to sole herbicide applications or twice hand weeding. They found that a combination of pre-emergence pendimethalin + metribuzin or pre-emergence pendimethalin + one-hand weeding provided the best weed control compared to other treatments. They also revealed that twice hand weeding and post-emergence herbicides or their mixtures were more effective than pre-emergence herbicides to control weeds.

PEP followed by hand weeding and hand weeding (alone) were the most effective treatments for weed control in 2023. Previous studies indicated that if pre-emergence herbicides such as oxyfluorfen and diclosulam are combined with hand-weeding, they may provide better weed control than hand-weeding alone or their solo usage (Ahmadi et al. 2024). In contrast, Deshmukh et al. (2020) found that twice-hand weeding outperformed all herbicide treatments in wheat, suggesting. This unexpected result is probably caused by selected herbicides and/or weather conditions.

Yield Response

The highest grain yields in 2021 and 2022 were recorded in PSG + hand weeding plots (5,142.3–6,513.0 kg ha^{-1}), followed by hand weeding alone (5,064.0–6,286.0 kg ha^{-1}) (Fig. 4). This indicates that maintaining weed-free conditions significantly enhances yield. The lowest yield was recorded in the weedy control with 3,787.5–4,710 kg ha^{-1}, showing the negative impact of weed competition on win-

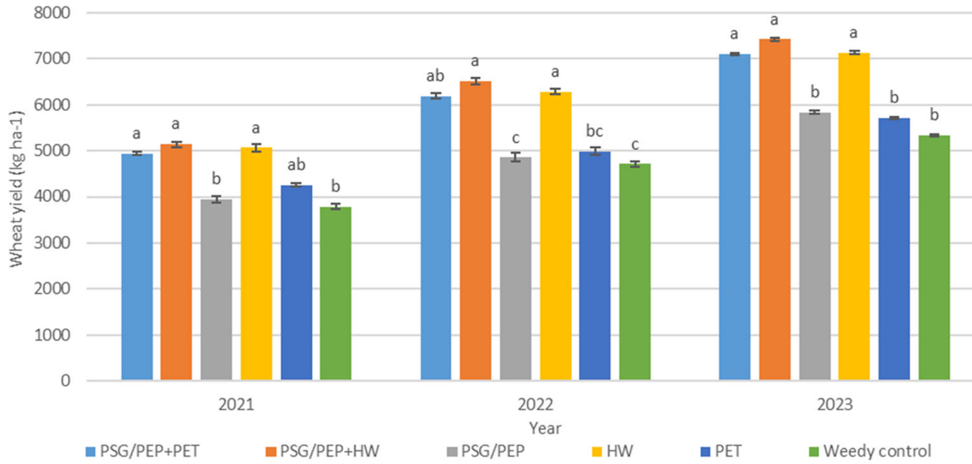

Fig. 4 Comparison of yield (kg ha^{-1}) across different weed control treatments in 2021–2023. Means were separated using Fisher's Protected Least Significant Difference (LSD) test at $P<0.05$. The bars represent mean yield values, with error bars indicating standard errors. (*PGS* Pre-sowing glyphosate, *PEP* Pre-emergence pyroxasulfone, *PET* Post-emergence tribenuron-methyl; *HW* Hand-weeding)

ter wheat productivity. Pre-sowing glyphosate followed by post-emergence tribenuron produced 687–1,197 kg ha^{-1} more yields than post-emergence tribenuron alone, suggesting that integrating pre-sowing glyphosate application improves weed control efficacy.

The yield difference between untreated (weedy) control and hand weeding treatments was substantial, with the weed-free treatment producing 33.8 and 33.5% higher yields in 2022 and 2023, respectively. These results are consistent with findings by Kleemann et al. (2016), who reported increased wheat yield following PEP application in no-till systems, and by Serim et al. (2025), who observed enhanced yields from pre-planting weed control in winter wheat.

Shah et al. (2025) reported that effective weed control treatments such as combinations of pre-emergence and post-emergence herbicides or hand weeding increased wheat grain yield compared to other treatments and non-treated control, similar to our findings. Our data support the previous research conducted by Kumar Naik et al. (2022), who indicated that the combination of pre-emergence herbicide with post-emergence herbicide effectively controlled most broadleaf weeds and some annual grasses in groundnut, and provided higher net return compared to the control.

Impact of PHG with and without Tribenuron-methyl Application On Weed Seed Bank

Nineteen weed species were identified in the soil seed bank such as *A. retroflexus, V. hederifola, P. oleracea, C. album, S. viridis, S. nigrum, S. media, P. aviculare, C. regalis, X. strumarium, Euphorbia* spp., *A. myosoroides, C. arvense, C. arvensis, F. officinalis, G. aparine, S. arvensis, S. italicus*, and *L. serriola*. The species composition and their density in the treated plots varied over the field trials compared to non-treated checks.

The data shows significant differences in weed seed count based on treatment type and year (Fig. 5). The conventional (untreated) plots consistently exhibited the highest weed seed densities across all years. PEP and PSG treatments significantly reduced seed densities of dominant species such as *A. retroflexus, P. oleracea*, and *C. album*. While *S. viridis* and *S. nigrum* seed densities increased slightly under PEP in some years, the overall seed bank pressure declined over time.

Comparing years, weed seed densities were generally higher in the first year and decreased slightly in the following years due to improved control or environmental influences affecting weed germination. For instance, *A. retroflexus* in PET treatment declined from 60.5 in 2021 to 48.5 in 2022 and further to 58.75 in 2023. Similarly, the density of *C. album* seeds remained near the initial level even if some fluctuations had been observed. Some weeds such as *V. hederifola* and *P. aviculare* were mainly present in lower densities in conventional treatments, but their densities significantly declined in PEP and PSG treatments. Among the weed species, *C. album* was the least affected weed species by weed control applications compared to other species in the soil seed bank.

Previous research indicated that weed seed banks are shaped by some factors, particularly weed species, soil tillage, herbicides, and cropping systems (Feledyn-Szewczyk et al. 2020; Sharshar et al. 2022; Rodriguez et al. 2024). The impact of herbicides on the soil seed banks varies depending on the herbicide type, herbicide rate, weed species, and environmental conditions. This effect, which is seen in our studies, aligns with the findings by Serim et al. (2025), who indicated that herbicides changed soil seed bank in winter wheat, by Schweizer and Zimdahl (1984), who showed that using atrazine during 6 concessive years declined weed seed number up to >90% in the soil seed bank, and by Šikuljak Pavlović et al. (2023), who found that combining mechanical weed control at three

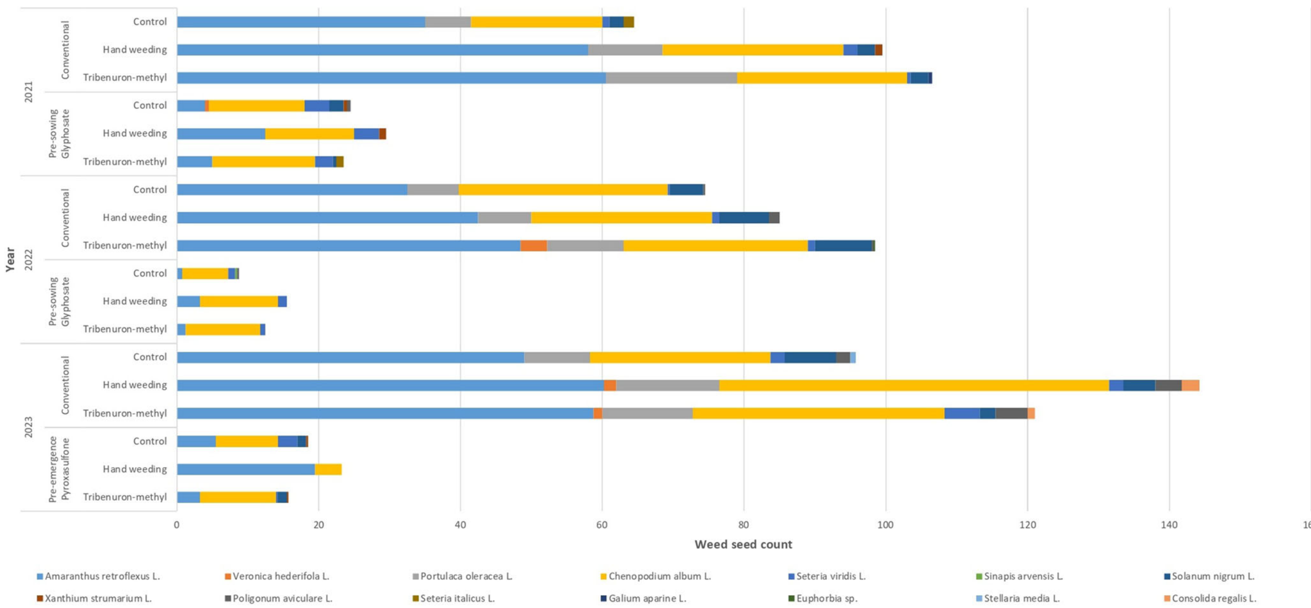

Fig. 5 Impact of weed control treatments on the weed seed bank (2021–2023)

times and pre-planting glyphosate treatment significantly declined weed soil seed bank in tomato compared to the mechanical weed control treatment. Our results also corroborate Davis et al. (2005), who reported that *C. album* was among the most persistent components of the soil seed bank.

Conclusion

Providing a weed-free environment for newly established wheat seedlings is crucial to obtain high grain yield. Pre-emergence or pre-sowing herbicides give a chance for these seedlings to grow without competition from weeds. Herbicide resistant and/or perennial weeds can no longer be easily controlled by one herbicide treatment in many wheat fields. Combining pre-sowing glyphosate treatment with post-emergence tribenuron-methyl or hand-weeding resulted in effective weed control and a considerable yield increase compared to conventional weed control treatment such as post-emergence tribenuron-methyl. On the other hand, pre-emergence pyroxasulfone had greater efficacy on weed flora because of the residual impact of pyroxasulfone compared to pre-sowing glyphosate. Another significant aspect of combining these herbicides or weed control treatments was observed in soil seed banks. Weed seed composition in the winter wheat field changed depending on the treatment. Similar to the effect on aboveground weeds, although all herbicide treatments, alone or combined with hand-weeding, reduced seed densities in the soil seed bank, pre-emergence pyroxasulfone and its combinations were the most effective.

Wheat farmers should follow the weed control experts' instructions to control troublesome weeds, especially in continuous monoculture winter wheat fields. Herbicide programs should be regularly revised using alternative selective and total herbicides belonging to different modes of action such as glufosinate, pendimethalin, or 2.4-D. These programs may be enhanced by adding remote sensing technologies and decision-support tools, particularly under variable climatic conditions that affect weed emergence and herbicide performance. By using real-time environmental data such as soil moisture and temperature, these programs may enable more accurate and weather-adaptive treatments.

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Author Contribution All authors contributed to the study conception and design. Material preparation, experimental conduction, data collection by Ünal Asav, Yalçın Kaya, Bülent Başaran and analysis were performed by Ahmet Tansel Serim. The the manuscript was written by Ünal Asav, Ahmet Tansel Serim, and all author approved the final manuscript.

Availability of Data and Material The data generated during the current study are available from the corresponding author on reasonable request.

Conflict of interest Ü. Asav, A.T. Serim,Y. Kaya and B. Başaran declare that they have no competing interests.

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