Evaluating the role of post-harvest glyphosate application in enhancing weed control in winter wheat (#109508)

First submission

Guidance from your Editor

Please submit by **26 Dec 2024** for the benefit of the authors (and your token reward) .

Structure and Criteria
Please read the 'Structure and Criteria' page for guidance.

Raw data check
Review the raw data.

Image check
Check that figures and images have not been inappropriately manipulated.

If this article is published your review will be made public. You can choose whether to sign your review. If uploading a PDF please remove any identifiable information (if you want to remain anonymous).

Files

Download and review all files from the materials page.

3 Figure file(s)
4 Table file(s)
1 Raw data file(s)

Structure and Criteria

Structure your review

The review form is divided into 5 sections. Please consider these when composing your review:

1. **BASIC REPORTING**
2. **EXPERIMENTAL DESIGN**
3. **VALIDITY OF THE FINDINGS**
4. General comments
5. Confidential notes to the editor

You can also annotate this PDF and upload it as part of your review

When ready submit online.

Editorial Criteria

Use these criteria points to structure your review. The full detailed editorial criteria is on your guidance page.

BASIC REPORTING

- Clear, unambiguous, professional English language used throughout.
- Intro & background to show context. Literature well referenced & relevant.
- Structure conforms to PeerJ standards, discipline norm, or improved for clarity.
- Figures are relevant, high quality, well labelled & described.
- Raw data supplied (see PeerJ policy).

EXPERIMENTAL DESIGN

- Original primary research within Scope of the journal.
- Research question well defined, relevant & meaningful. It is stated how the research fills an identified knowledge gap.
- Rigorous investigation performed to a high technical & ethical standard.
- Methods described with sufficient detail & information to replicate.

VALIDITY OF THE FINDINGS

- **Impact and novelty is not assessed.** Meaningful replication encouraged where rationale & benefit to literature is clearly stated.
- All underlying data have been provided; they are robust, statistically sound, & controlled.
- Conclusions are well stated, linked to original research question & limited to supporting results.

Standout reviewing tips

The best reviewers use these techniques

Tip	*Example*
Support criticisms with evidence from the text or from other sources	*Smith et al (J of Methodology, 2005, V3, pp 123) have shown that the analysis you use in Lines 241-250 is not the most appropriate for this situation. Please explain why you used this method.*
Give specific suggestions on how to improve the manuscript	*Your introduction needs more detail. I suggest that you improve the description at lines 57- 86 to provide more justification for your study (specifically, you should expand upon the knowledge gap being filled).*
Comment on language and grammar issues	*The English language should be improved to ensure that an international audience can clearly understand your text. Some examples where the language could be improved include lines 23, 77, 121, 128 – the current phrasing makes comprehension difficult. I suggest you have a colleague who is proficient in English and familiar with the subject matter review your manuscript, or contact a professional editing service.*
Organize by importance of the issues, and number your points	*1. Your most important issue* *2. The next most important item* *3. …* *4. The least important points*
Please provide constructive criticism, and avoid personal opinions	*I thank you for providing the raw data, however your supplemental files need more descriptive metadata identifiers to be useful to future readers. Although your results are compelling, the data analysis should be improved in the following ways: AA, BB, CC*
Comment on strengths (as well as weaknesses) of the manuscript	*I commend the authors for their extensive data set, compiled over many years of detailed fieldwork. In addition, the manuscript is clearly written in professional, unambiguous language. If there is a weakness, it is in the statistical analysis (as I have noted above) which should be improved upon before Acceptance.*

Evaluating the role of post-harvest glyphosate application in enhancing weed control in winter wheat

Ahmet Tansel Serim Corresp., 1 , **Ünal Asav** 2 , **Yalçın Kaya** 3 , **Bülent Başaran** 3

1 Department of Plant Protection, Bilecik Seyh Edebali University, Bilecik, Turkey

2 Department of Plant Protection, Gaziosmanpasa University, Tokat, Turkey

3 Middle Black Sea Transitional Zone Agricultural Research Institute, Tokat, Turkey

Corresponding Author: Ahmet Tansel Serim
Email address: ahmettansel.serim@bilecik.edu.tr

Changes in the timing and intensity of spring rainfall have led to a significant increase in late-season weed emergence in Türkiye. These newly emerging weeds tend to grow more vigorously due to the absence of competition with crops and other weeds during their development. Under favorable conditions, they produce more seeds than those that emerge during the regular cropping season and contribute to the enrichment of the soil weed seed bank. Two field experiments were conducted over four years (2020–2023) in Türkiye. The first was to determine the impact of post-harvest herbicide (PHH) on the critical time for weed removal (CTWR) in winter wheat, and the latter was to evaluate the effects of PHH combined with various weed control treatments on weed populations, the soil seed bank, and crop yield. The experiment followed a split-plot design, with the PHH regime and weed removal timing or weed control treatments serving as the main and sub-plots, respectively. The herbicide regime included no PHH and post-harvest glyphosate (PHG) applied at 2.646 kg ai ha^{-1}. Weed removal timings were set at 10-day intervals, from 0 to 110 days after wheat emergence (DAE). Weedy and weed-free controls were included for comparison. Weed control treatments involved post-emergence tribenuron-methyl at 11.25 g ai ha^{-1} and hand weeding. The application of PHG delayed the CTWR from 416 growing degree days (GDD) to 516.5 GDD in 2022, and from 465.6 GDD to 661.2 GDD in 2023, effectively preventing yield loss. The combined use of PHG with post-emergence tribenuron-methyl or hand weeding maximized wheat yield while minimizing the soil seed bank.

Evaluating the Role of Post-Harvest Glyphosate Application in Enhancing Weed Control in Winter Wheat

Ahmet Tansel Serim[1], Ünal Asav[2], Yalçın Kaya[3], Bülent Başaran[3]

[1] Bilecik Seyh Edebali University, Faculty of Agriculture and Natural Sciences, Department of Plant Protection, Bilecik-Turkey
[2] Tokat Gaziosmanpaşa University, Faculty of Agriculture, Department of Plant Protection, Tokat-Turkey
[3] Middle Black Sea Transitional Zone Agricultural Research Institute, Tokat-Turkey

Corresponding author:
Ahmet Tansel SERİM,
Bilecik Seyh Edebali University, Faculty of Agriculture and Natural Sciences, Department of Plant Protection, Bilecik-Turkey
ahmettansel.serim@bilecik.edu.tr

Abstract

Changes in the timing and intensity of spring rainfall have led to a significant increase in late-season weed emergence in Türkiye. These newly emerging weeds tend to grow more vigorously due to the absence of competition with crops and other weeds during their development. Under favorable conditions, they produce more seeds than those that emerge during the regular cropping season and contribute to the enrichment of the soil weed seed bank. Two field experiments were conducted over four years (2020–2023) in Türkiye. The first was to determine the impact of post-harvest herbicide (PHH) on the critical time for weed removal (CTWR) in winter wheat, and the latter was to evaluate the effects of PHH combined with various weed control treatments on weed populations, the soil seed bank, and crop yield. The experiment followed a split-plot design, with the PHH regime and weed removal timing or weed control treatments serving as the main and sub-plots, respectively. The herbicide regime included no PHH and post-harvest glyphosate (PHG) applied at 2.646 kg ai ha^{-1}. Weed removal timings were set at 10-day intervals, from 0 to 110 days after wheat emergence (DAE). Weedy and weed-free controls were included for comparison. Weed control treatments involved post-emergence tribenuron-methyl at 11.25 g ai ha^{-1} and hand weeding. The application of PHG delayed the CTWR from 416 growing degree days (GDD) to 516.5 GDD in 2022, and from 465.6 GDD to 661.2 GDD in 2023, effectively preventing yield loss. The combined use of PHG with post-emergence tribenuron-methyl or hand weeding maximized wheat yield while minimizing the soil seed bank.

Key words: Critical time of weed removal, winter wheat, post-harvest herbicide, glyphosate, tribenuron-methyl, Growth degree day, soil seed bank

Introduction

Wheat is a valuable staple crop for humanity because it provides the main dietary energy and protein for one in five people in the world (Erestein et al., 2022). Its prominence is mainly rooted in some comprehensible reasons, such as adaptability to diverse climates, easy husbandry practices, and flexibility to adverse conditions. Contrary to these superiorities to other crops, extreme weather events, pests, diseases, and weeds often prevent high grain yield expectations (Moa et al., 2023). Weeds are generally considered strong competitors to wheat, and they result in severe yield losses depending on weed species, density, and competition timing (Peairs et al., 2005). To mitigate these undesirable impacts, many weed control treatments, including biological, cultural, mechanical, physical, and chemical techniques are commonly used by farmers.

To address these challenges, cultural weed control is successfully employed in many fields (Beres et al., 2010; Peairs et al., 2005), but the widespread use of this technique is often constrained by low rainfall or the inability to provide workers. Chemical weed control by herbicides, on the other hand, may allow growers to control them easily and cost-effectively (Coleman et al., 2019) and therefore make themselves an indispensable tool for many growers. Herbicide use was launched in wheat fields (Coleman et al., 2019; Peairs et al., 2005) and has never lost its popularity among wheat growers until the last decades.

The incessant use of herbicides has led to some adverse side effects such as carryover, runoff, drift, biodiversity loss, and herbicide-resistant weeds, especially in many wheat-producing regions (Wang et al., 2022; Türkseven et al., 2022). For example, there have been 533 documented cases of herbicide-resistant weeds worldwide, more than half of them in wheat fields (Heap, 2024). In Turkey, they are also becoming widespread in wheat fields, with five species reported to be resistant to ALS and/or ACCase inhibitor herbicides (Heap, 2024). Herbicide-resistant weeds and side effects of wheat herbicides threaten the sustainability of wheat production and therefore force researchers to find new alternatives. Growers often apply herbicides in a mixture, overrate, or repeat them to control herbicide-resistant weeds, but this approach raises the cost. At this point, pre-sowing and post-harvest herbicide applications might increase weed control efficacy while decreasing the risk related to the appearance of new herbicide-resistant weeds in crops.

Total herbicide use at pre-sowing or pre-emergence is a powerful approach to control weeds presented in the fields due to reducing weed pressure during the early growth stage. Doğan et al. (2009) demonstrated improved weed control and cotton yield with glyphosate compared to conventional pre-emergence herbicides. Similarly, pre-sowing, pre-emergence, and post-harvest glyphosate applications are commonly used to control weeds and volunteers in annual cropping systems such as cereals, maize, legumes, and sugar beet, in many European countries (Antier et al., 2020). However, some weeds may continue to grow in stubble after harvest and disperse their seeds. Post-harvest glyphosate application suppresses the growth of these weeds and reduces seed production (Crow et al., 2015).

Because of its protective structure, soil acts as a natural vault for weed seeds and influences the makeup of weeds in succeeding crops. The weed seed bank is affected by several factors such as crop rotation, soil characteristics, and weed management techniques (Jabran and Chauhan, 2015; Osipitan et al., 2018; Skuodiene et al., 2024; Schwartz-Lazaro and Copes, 2019). For instance, Michelson et al. (2004) indicated that post-harvest glyphosate application reduced Kochia seed production by up to 99%. However, the impact of post-harvest glyphosate, alone or in combination with post-emergence herbicide on the weed seed bank in wheat production has not been thoroughly investigated in the literature.

Critical time for weed removal (CTWR) is the beginning of the critical period of weed control, which is a useful tool in integrated weed management strategies. CTWR provides valuable knowledge to the growers about when weed control efforts should be implemented to prevent yield losses. Indeed, previous studies showed that CTWR in wheat typically spans the first 4 weeks after crop emergence (Jabran et al., 2015). Pre-sowing glyphosate application in no-till maize effectively eliminates weeds and postpones CTWR for up to 17 days (Adamič Zamljen and Leskovšek, 2023). Similar findings were also reported by Roncatto et al. (2023) in soybean, Ulusoy et al. (2020) in corn, Knezevic et al. (2013) in sunflower, and Barnes et al. (2019) in popcorn. Although post-harvest herbicide applications control weeds and weed seed production in stubble, the impact of them on the CTWR has not been studied.

Spring rainfall patterns in Anatolia have changed weed emergence and growth in recent years. This change resulted in getting out of some weeds from post-emergence herbicides, and continued weed seed production. For instance, cumulative rainfall in June increased by 44-78% during 2021-2023 compared to the long-term records of Kazova, Tokat, Turkey (Table 1). Some weeds could not complete their life cycle when wheat reaches harvest time. Therefore, these wheat fields are abandoned in many areas. A comprehensive weed management approach, such as involving post-harvest glyphosate applications, followed by post-emergence herbicide or hand weeding, may be necessary to effectively manage the dynamic weed flora in wheat production systems. This study aimed to determine the effectiveness of post-harvest glyphosate application on weeds, wheat grain yield, the weed seed bank, and the CTWR in wheat.

Material and Methods

Experimental field and environmental conditions

Field experiments were conducted at the Middle Black Sea Transaction Zone Agricultural Research Institute (40.1928N; 36.2656E), Tokat, Turkey, from 2000 to 2023. The soil was clay loam with 1.5% organic matter and a pH of 7.9. The 'Flamura-85' wheat variety was sown at a seeding rate of 500 seeds m^{-2} during October-November. This variety is widely cultivated in the central Anatolian region and is known to be resistant to cold and lodging. The weed flora of the experimental field was determined when the weeds reached the flowering stage each year.
Kazova has a continental climate with distinct seasonal variations. The coldest month is January at -1.6°C, while the warmest month is August at 29.9°C. The first frost was typically recorded in October or November, and the last frost was in May. The annual average number of rainy days was 103.8, with 431.7 mm. April, May, and June were generally the wettest months, whereas the least rainfall was recorded in July and August. Specific climate data collected during the experiment are shown in Table 1.

Research Design and Treatments:
Impact of herbicide programs on weed flora and wheat yield

The study was designed as a split-plot experiment with four replications. The main plots were assigned to herbicide regime post-harvest glyphosate (PHG) treatment and no PHG, and the subplots were allocated to the weed control treatments. Each plot was 3m x 3.5m. A 2 m alley was left between blocks, and a 1 m alley was left between parcels (Figure 1A). The treatments were: T1: PHG + Post-emergence tribenuron-methyl, T2: PHG + Weedy check, T3: No PHG + Post-emergence tribenuron-methyl, T4: No PHG + Weedy check, PHG + Hand weeding (T5), and No PHG + Hand weeding (T6). Hand weeding was employed 3 times with 10 days' intervals after the tillering began.
Glyphosate potassium salt and tribenuron-methyl were applied using a field sprayer and motorized backpack sprayer adjusted to deliver 200 l ha^{-1} at 200 kPa pressure, respectively (Figure 1B and 1C). Glyphosate was applied at 2.646 kg ai ha^{-1} one week after wheat harvest as a post-harvest

treatment to control grass and broadleaf weeds in the stubble. Tribenuron-methyl was applied at a rate of 11.25 g ai ha^{-1} at the 3-4 leaf stage of the wheat crop to control broadleaf weeds.
Weed flora was determined at the end of April when winter wheat reached the tillering stage. Weeds in each plot were recorded from 1 m^2 and identified according to the Flora of Turkey and the North Aegean Islands (Davis, 1965-1985). During the harvest time, ears in a 1 m^2 area were harvested from each plot. The harvested ears were placed in bags, brought to the laboratory, and threshed. The grain yield was calculated on a per-hectare basis by converting the results from the harvest area.
The collected data on wheat grain yield were subjected to variance analysis using the Agricolae package (Mendiburu and Yaseen, 2020) in the R statistical software (RStudio Team. 2024). The means were compared using the Least Significant Difference test at the 5% probability level. Wheat yield data were separately subjected to ANOVA for each year because post-harvest herbicide treatment by weed control treatment interactions were significantly different ($P \leq 0.05$).

Impact of PHG with and without tribenuron-methyl application on weed seed bank
The weed seed bank was determined by separating all seeds from soil samples containing debris and soil particles. Soil samples were collected from each plot using a soil borer (5 cm diameter) at 10 cm soil depth. The soil samples were first sieved (4 mm x 4 mm) to remove unwanted materials, then sieved using a precise sieve (0.25 mm x 0.25 mm) to separate soil aggregates. Soil samples were put in a plastic bucket filled with tap water and left for 24 hours (Figure 1D). The slurry was gently mixed and washed using a sieve set under tap water. 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).
The impact of PHG and weed control treatments on AWSD data was subjected to variance analysis using the Agricolae package (Mendiburu and Yaseen, 2020) in the R statistical software (RStudio Team. 2024). The means were compared using the Least Significant Difference test at the 5% probability level to determine the statistical significance of the differences among the treatments. AWSD data were separately subjected to ANOVA for each year because year, PHG treatment by weed control treatment interactions were significantly different ($P \leq 0.05$).

Impact of PHG on CTWR
The CTWR in wheat was calculated by assessing the relationship between wheat grain yield and the duration of weed presence during the growing season. In the weedy control treatment, weeds were allowed to compete with the crop for the entire season, while in the weed-free control, weeds were removed manually at 10-day intervals to prevent competition with the crop. Weed removal times were adjusted at 10-day intervals, from 0 to 110 days after wheat emergence (DAE). The grain yield obtained from the weed-free control treatment was considered the maximum yield, and the percentage yield loss was calculated by comparing the grain yield from the weedy control treatment to the weed-free control.

The experiment was carried out for three consecutive years. The experimental design was a split-block design with three replications, where the main plots were assigned to the PHG and No PHG, and the subplots were allocated to the length of the weed-free period, weed-free, and weedy season-long controls. Each subplot was 2 m x 3 m. A non-linear regression analysis was performed on the yield loss data to model the relationship between weed presence duration and wheat grain yield. The log-logistic model was then used to estimate the CTWR (Formula 1).

$$Y = c + \frac{d - c}{1 + \exp\left(b(\log(x) - \log(GR50))\right)} \quad (1)$$

where Y is grain yield; C is the lower limit; D is the upper limit; X is weed removal timing expressed in growing degree days (GDD) after wheat emergence, E is the GDD at the inflection point (I_{50}), and B is the slope around the I_{50}. GDD was calculated according to the formula 2.

$$GDD = \Sigma\left[\frac{Tmax + Tmin}{2}\right] - Tbase \quad (2)$$

Where GDD, T_{max}, T_{min}, and T_{base} were growing degree day, daily maximum temperature, daily minimum temperature, and base temperature (≥0ºC) for wheat growth, respectively. The data are presented separately for each year because the year and herbicide treatment interaction was not significant.

Results and Discussion

Impact of herbicide program on weed flora and wheat yield

The experimental field consisted of 15 weed species, most of which were annual dicotyledonous (Table 2). The most prevalent weeds were *Veronica hederifolia* L., *Chenopodium album* L., and *Amaranthus retroflexus* L. in the experimental field. The composition and density of weed species in the herbicide-treated and untreated plots varied over the field trials. Post-emergence tribenuron-methyl killed many of *V. hederifolia* and *A. retroflexus* similar to other weed species, such as *Sinapis arvensis* L., *Galium aparine* L., *Fumaria officinalis* L., *Portulaca oleracea* L., and *Seteria viridis* L. Likewise, PHG application alone resulted in a considerable reduction in these weeds. In parcels applied with post-emergence tribenuron-methyl or PHG, weed density showed a slight decline over time, except in the PHG parcels in the third year. This unexpected increase might be attributed to the heavy rainfall that occurred in April 2023 (Table 1). The most significant reduction in weed densities was observed in parcels treated with a PHG + post-emergence tribenuron-methyl. Specifically, the PHG + post-emergence tribenuron-methyl had a powerful impact on *V. hederifolia*, and declined its density by 44%, 71%, and 90.9% in 2021, 2022, and 2023, respectively. Similarly, *A. retroflexus* density was declined by PHG + post-emergence tribenuron-methyl up to 76.2%. Additionally, this treatment controlled several other weed species such as including *F. officinalis*, *G. aparine*, *S. arvensis*, *Polygonum aviculare* L., *P. oleracea*, *L. serriola*, and *S. viridis*. On the other hand, herbicide treatments unexpectedly increased *C. album* populations over the three years.

Previous studies have shown that weed control treatments such as tillage or herbicides might alter weed flora in agricultural fields (Torrosen et al., 2003; Shahzad et al., 2016; Ball and Miller, 1993).

The strong impact of herbicides on weed density and diversity in wheat fields was reported by Culpepper (2006), Shahzad et al. (2021), Wilson et al. (2007), and Barnes et al. (2019). Young and Thorne (2004) stated that the use of late-season herbicide in no-till caused a significant weed shift, and *Salsola iberica* became the prevalent weed species in the field. Contrary, Reddy et al. (2015) showed that there was no meaningful impact of post-harvest herbicide treatment (Pendimethalin+Paraquat) on the weeds compared to no herbicide treatment. This discrepancy might be caused by used herbicides, or weeds in the flora. Specifically, PHG application was particularly effective in reducing the density of VERHE and AMARE, both of which were less prevalent after the herbicide treatment. This application effectively suppressed the dominance of these weeds, and provided favorable conditions for the proliferation of CHEAL, as the reduced competition allowed CHEAL to become the primary weed, similar to the results of Wilson et al. (2017).

The PHG + hand weeding treatment resulted in the highest wheat grain yield of 5.2-7.5 t ha^{-1}, which meant 37-41% higher than the weedy control (Figure 2). In comparison, PHG + tribenuron-methyl treatment was as effective as at least PHG + hand weeding application with 5.1-7.2 t ha^{-1} grain yield. Furthermore, No PHG + hand weeding led to good weed control. However, No PHG + tribenuron-methyl application or PHG provided only moderate weed control and resulted in a 17-25% lower wheat yield than the PHG + hand-weeding treatment. Altogether, this result indicated that using PHG was effective as a post-emergence herbicide to control weeds in the winter wheat.

Across all treatments, yields tend to improve over the three years (2020 to 2022), suggesting that most treatments are having a positive impact, even though the differences between them are statistically significant. The effect of PHG + hand weeding or PHG + post-emergence tribenuron-methyl on the wheat yield was limited over time compared to weedy check; however, this impact was statistically noticeable in the post-harvest glyphosate applications or only post-emergence tribenuron-methyl application. This indicates that PHG applications for 3 years provide a yield increase depending on the time.

There is a strong negative relationship between weed abundance and crop yields, whereby an increase in weed density directly impacts the productivity of crops. Weed-crop competition can significantly hinder crop development, leading to lower yields. In other words, the higher the weed pressure, the greater the yield loss. Consistent with this, former studies indicated that PHG was a powerful tool for controlling many problematic weeds in crops during the late season (Young and Gealy, 1986; Kumar and Jha, 2015). For example, Kumar et al. (2021) indicated that PHG application at 1,260 g ae/ha controlled palmer amaranth at 93% 8 weeks after treatment. Similarly, Young and Gealy (1986) found that post-harvest weed control not only reduces weed seeds and ground-above biomass but also saves soil moisture for subsequent crops. This finding particularly explained the yield increase in plots treated with PHG.

Even though post-harvest glyphosate application suppressed weed competition and increased wheat yield, this impact was limited because of the non-residual impact of glyphosate. Maintaining weed control impact of herbicides can be possible through herbicide application programs like post-harvest glyphosate followed by selective herbicides or tillage. Consistent with our findings, Bae et al. (2022) reported that post-harvest herbicide (Diclobenil) along with post-emergence herbicides (Clopyralid/ Mesotrione followed by Mesotrione + Sethoxydim) on *Equisetum arvense* L. was 47-52% more effective than only post-emergence herbicide (Clopyralid/ Mesotrione followed by Mesotrione + Sethoxydim). A similar study by Meyers et al. (2016) supports our findings, demonstrating that an herbicide program incorporating post-harvest application of flumioxazin achieved greater control of the problematic weeds compared to a program without post-harvest treatment.

Impact of PHG with and without tribenuron-methyl application on weed seed bank

PHG + post-emergence tribenuron-methyl and PHG + hand weeding treatments significantly reduced Average Weed Seed Density (AWSD) compared to the weedy control (Table 3). PHG + post-emergence tribenuron-methyl declined AWSD by 77.9%, indicating highly effective long-term weed suppression. This meant a considerable reduction compared to the seed number (9.8) in 2021. Similarly, PHG + hand weeding resulted in a significant decline in AWSD from 13.7 seeds/soil sample in 2021 to 7.7 seeds/soil sample in 2023. This decline may be caused by the synergistic impact of PHG and post-emergence weed control treatments (tribenuron-methyl or hand weeding) due to preventing the life cycle of weeds. However, PHG, hand weeding, or tribenuron-methyl applications could not prevent AWSD increase over the experiment. For instance, AWSD in PHG plots increased 2.76 times in 2023 compared to 2021, whereas a 2.93 times higher increase was observed in conventional plots. This increase was an expected result since glyphosate has no residual impact to cover a season.

Kumar et al. (2021) showed late-season total herbicide treatments such as glyphosate, dicamba, paraquat, and glufosinate reduced palmer amaranth seed production by more than 90%. Similarly, in another study, Mickelson et al. (2004) reported that PHG application at 631 g ha^{-1} resulted in a reduction in Kochia seed production by up to 99%. Furthermore, Kumar and Jha (2015) reported that post-harvest herbicide application could reduce seed production of *Kochia scoparia* by 32-100% depending on the herbicide and the combinations used. Additionally, Maity et al. (2022) also showed that harvest weed seed control tactics followed 4 years declined *Lolium perenne* ssp. *multiflorum* seeds similar to our results.

In our study, the effect of PHG, with or without post-emergence tribenuron-methyl, was lower than reported in previous studies. This discrepancy is likely due to the fact that we evaluated the impact on all weed species present, rather than focusing on a single species. Moreover, certain weeds, such as CHEAL, were less affected by PHG compared to other species. This case provides an advantage to it to continue growing and producing seeds despite PHG.

Impact of PHG on Critical time for weed removal

Experimental fields consisted of 15 weed species that were predominantly broadleaf weeds, including *Chenopodium album, Amaranthus retroflexus., Convolvulus arvensis*, and *Veronica* *hederifolia* (Table 1). While grassy weeds, such as *Alopecurus myosoroides* and *Seteria viridis* were also present, they occurred at relatively lower densities compared to the broadleaf weed.

Wheat yield loss

Wheat yield losses were affected by weed removal timing, PHG, and years (Figure 3). Wheat yield declined with increasing duration of weed interference during 2021-2023. Grain yield in season-long weed-free plots with PHG was 5.127 t ha^{-1} in 2021, 7.668 t ha^{-1} in 2022, and 7.120 t ha^{-1} in 2023, respectively. Wheat yield in season-long weedy plots with PHG was 46.1, 75.5, and 71.2% lower than in season-long weed-free plots. Similarly, the yield in season-long weed-free plots without PHG was 5.211 t ha^{-1}, 6.510 t ha^{-1}, and 6.635 t ha^{-1} in the same period, respectively. Wheat yield in season-long weedy plots without PHG was 51.3, 47.5, and 76.6% lower than in season-long weed-free plots. Notably, the smallest yield decrease was observed in 2022 compared to 2021 and 2023, mainly due to weed presence and reduced rainfall (38.93% lower than the average).
Wheat yield loss due to weeds was reported as 2.9-34.4% in the USA, 2.9% in Canada, and 20-32% in Pakistan (Flessner et al., 2021; Chhokar et al., 2012). These rates were lower than our results, mainly caused by weed flora and rainfall. Under soil moisture deficiency like ours, competition between weeds and wheat for limited resources is more destructive for wheat than under favorable conditions (Ihsan et al., 2015). Webster et al. (1998) investigated the impact of post-harvest herbicide application (Glyphosate+2,4-D) at three application times on corn yield and weed biomass in the corn field grown in the winter wheat-corn cropping system. They found that weed biomass was significantly reduced by post-harvest herbicide application without any herbicide treatment as corn yield was 2.75 times higher than non-treated control similar to our findings.

Critical time for weed removal

The CTWR was calculated using the log-logistic model described based on a 5% acceptable yield loss by Ritz et al. (2015). In the first year of the study, the CTWR began at nearly the same point in both No PHG and PHG treatment (Table 4, Figure 3). Specifically, the CTWR was initiated at 711.9 growth degree days (GDD) in the conventional system and 718.5 GDD in the PHG parcels, showing minimal difference between the two treatments in terms of the onset of critical weed pressure. In contrast, the apparent effect of PHG on CTWR was observed in the second year. In 2022, the CTWR started at 416 GDD, which corresponds to 16.6 DAE in the No PHG; meanwhile, the CTWR was delayed until 516.5 GDD (22.3 DAE) in the PHG parcels. The PHG treatment delayed the CTWR from 465.6 GDD (14.5 DAE) to 661.2 GDD, equivalent to 31.6 DAE in 2023. This means a substantial delay of 17.1 days compared to the control.
Previous studies have shown that CTWR varied according to numerous factors, including growing season, crop species, agronomic practice, and environmental factors (Contreras et al., 2022). However, a few studies about CTWR in wheat were found in the literature. The CTWR started 2-3 weeks after seed emergence or 28 or 30 days after sowing (Agostinetto et al., 2008; Morsy et al.,

2020; Chaudhary et al., 2008). These times are in agreement with our results, which varied 16.6-31.4 DAE in No PHG.

The relationship between weed abundance and CTWR has been reported in many crops (Charles et al., 2019 and 2020; Williams et al., 2007). The results of nearly all are more or less the same as weed density decreases, CTWR is delayed. To reduce weed density in crops, total herbicides might be used at various times, such as pre-sowing, pre-emergence, or post-harvest. These treatments improve weed suppression throughout stubble or the early growth stages and alter the CTWR. Pre-emergence herbicide treatments delayed CTWR by 15-21 d in soybean (Roncatto et al., 2023), by 3-21 d in corn (Ulusoy et al., 2020), by 29 d in dry bean, by 6-12 d in sunflower (Knezevic et al., 2013), by 22 d in dry bean (Beiermann et al., 2022), and by 25-32 d in popcorn (Barnes et al., 2019). The impact of PHG treatment on CTWR in our study, 5.7-17.1 d, was aligned with these studies.

Conclusions

This research showed that PHG application resulted in a gradual delay in the CTWR over the three years, particularly in the second and third years. The 5.6-day delay in 2022 and the 17.1-day delay in 2023 indicated how PHG can control weed growth and prolong the time before weed control practices. This delay provided by PHG may offer farmers a longer period to manage weeds in winter wheat. During this time frame, wheat crops continue to grow unless weed competition.

PHG is a powerful tool to control many weeds in winter wheat and has the potency to substitute for post-emergence herbicides. This approach is particularly important in terms of preventing herbicide drift when winter wheat is grown adjacent to sensitive crops such as sunflower, sugar beet, legumes, and vegetables. Moreover, if PHG is combined with post-emergence herbicide or hand weeding, it significantly improves grain yield while reducing weed density, and also weed seed density in the soil compared to conventional treatment.

Integrated PHG into conventional weed control practice in winter wheat can be a good alternative to control herbicide-resistant weeds without any extra effort or cost. Additionally, PHG + post-emergence herbicide or hand-weeding can be a more efficient tool to control the soil seed bank and decrease weed pressure in the next crop. PHG is therewithal a promising approach to keeping moisture and nutrients in the soil for subsequent crops, especially in semi-arid and arid regions. This treatment may reduce soil tillage for preparing seed beds because it kills stubble weeds.

References

Adamič Zamljen S, Leskovšek R. 2024. Critical period of weed control in maize as influenced by soil tillage practices and glyphosate application. *Agronomy* 14:93. https://doi.org/10.3390/agronomy14010093.

Agostinetto D, Rigoli R, Schaedler C, Tironi S, Santos L. 2008. Critical period for weed competition with wheat. *Planta Daninha* 26(2):271–278.

Antier C, Andersson R, Auskalnienė O, Barić K, Baret P, Besenhofer G, et al. 2020. A survey on the uses of glyphosate in European countries. *INRAE.* DOI: 10.15454/A30K-D531.

Bae J, Young N, Elsby M, Critchley R. 2022. Assessing an herbicide layering strategy in newly renovated and established cranberry fields. *2022 Research Project Report.* Available at: https://www.bccranberries.com/wp-content/uploads/2023/03/Research-Project-Report-2022_Jichul_Bae.pdf.

Ball DA, Miller SD. 1993. Cropping history, tillage, and herbicide effects on weed flora composition in irrigated corn. *Agronomy Journal* 85:817–821. DOI: 10.2134/agronj1993.00021962008500040007x.

Barnes ER, Knezevic SZ, Lawrence NC, Irmak S, Rodriguez O, Jhala AJ. 2019. Preemergence herbicide delays the critical time of weed removal in popcorn. *Weed Technology* 33(6):785–793. doi:10.1017/wet.2019.58

Barnes ER, Knezevic SZ, Lawrence NC, Irmak S, Rodriguez O, Jhala AJ. 2019. Preemergence herbicide delays the critical time of weed removal in popcorn. *Weed Technology* 33(6):785–793. DOI: 10.1017/wet.2019.58.

Beiermann CW, Miranda JWA, Creech CF, et al. 2022. Critical timing of weed removal in dry bean as influenced by the use of preemergence herbicides. *Weed Technology* 36(1):168–176. doi:10.1017/wet.2021.99

Beres BL, Clayton GW, Harker KN, Stevenson FC, Blackshaw RE, Graf RJ. 2010. A sustainable management package to improve winter wheat production and competition with weeds. *Agronomy Journal* 102:649–657. DOI: 10.2134/agronj2009.0336.

Charles GW, Sindel BM, Cowie AL, Knox OGG. 2019. Determining the critical period for weed control in high-yielding cotton using common sunflower as a mimic weed. *Weed Technology* 33(6):800–807. doi:10.1017/wet.2019.68

Charles GW, Sindel BM, Cowie AL, Knox OGG. 2020. Determining the critical period for grass control in high-yielding cotton using Japanese millet as a mimic weed. *Weed Technology* 34(2):292–300. doi:10.1017/wet.2019.113

Chaudhary SU, Hussain M, Ali MA, Igbal J. 2007. Effect of weed competition period on yield and yield components of wheat. *J Agric Res* 46(1):47–53.

Chhokar RS, Sharma RK, Sharma I. 2012. Weed management strategies in wheat – a review. *Journal of Wheat Research* 4(2):1–21.

Coleman GRY, Stead A, Rigter MP, Xu Z, Johnson D, Brooker GM, Walsh MJ. 2019. Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. *Weed Technology* 33(4):633–650. doi:10.1017/wet.2019.32

Contreras D, Leon RG, Post AR, Everman WJ. 2022. Critical period of grass weed control in ALS-tolerant grain sorghum (Sorghum bicolor) is affected by planting date and environment. *Front Agron* 4:1014801. doi:10.3389/fagro.2022.1014801

Crow WD, Steckel LE, Hayes RM, Mueller TC. 2015. Evaluation of post-harvest herbicide applications for seed prevention of glyphosate-resistant Palmer amaranth (Amaranthus palmeri). *Weed Technology* 29(3):405–411. doi:10.1614/WT-D-14-00146.1

Culpepper AS. 2006. Glyphosate-induced weed shifts. *Weed Technol* 20:277–281.

Davis PH (Ed.). 1965–1985. *Flora of Turkey and the East Aegean Islands.* Vols. 1–9. Edinburgh University Press, Edinburgh.

Dogan MN, Ünay A, Boz O, Ögüt D. 2009. Effect of pre-sowing and pre-emergence glyphosate applications on weeds in stale seedbed cotton. *Crop Protection* 28(6):503–507.

Erenstein O, Jaleta M, Mottaleb KA, Sonder K, Donovan J, Braun HJ. 2022. Global trends in wheat production, consumption and trade. In: Reynolds MP, Braun HJ (eds) *Wheat Improvement.* Springer, Cham. doi:10.1007/978-3-030-90673-3_4

Flessner ML, Burke IC, Dille JA, et al. 2021. Potential wheat yield loss due to weeds in the United States and Canada. *Weed Technology* 35(6):916–923. doi:10.1017/wet.2021.78

Heap I. The International Herbicide-Resistant Weed Database. Online. Monday, November 18, 2024. Available at www.weedscience.org.

Ihsan MZ, El-nakhlawy FS, Ismail SM. 2015. Water use efficiency, growth and yield of wheat cultivated under competition with setaria. *Planta Daninha* 33(4):679–687.

Jabran H, Chauhan BS. 2015. Weed management in aerobic rice systems. *Crop Protection* 78:151–163.

James A, Mickelson AJ, Bussan AL, Davis ES, Hulting AG, Dyer WE. 2004. Postharvest kochia (*Kochia scoparia*) management with herbicides in small grains. *Weed Technology* 18(2):426–431. http://www.jstor.org/stable/3989237.

Knezevic SZ, Elezovic I, Datta A, Vrbnicanin S, Glamoclija D, Simic M, Malidza G. 2013. Delay in the critical time for weed removal in imidazolinone-resistant sunflower (Helianthus annuus) caused by application of pre-emergence herbicide. *International Journal of Pest Management* 59(3):229–235. https://doi.org/10.1080/09670874.2013.830797

Knezevic SZ, Elezovic I, Datta A, Vrbnicanin S, Glamoclija D, Simic M, Malidza G. 2013. Delay in the critical time for weed removal in imidazolinone-resistant sunflower (*Helianthus annuus*) caused by application of pre-emergence herbicide. *International Journal of Pest Management* 59(3):229–235. DOI: 10.1080/09670874.2013.830797.

Kumar V, Jha P. 2015. Influence of herbicides applied postharvest in wheat stubble on control, fecundity, and progeny fitness of *Kochia scoparia* in the US Great Plains. *Crop Protection* 71:144–149.

Kumar V, Liu R, Jhala AJ, Jha P, Manuchehri M. 2021. Palmer amaranth (*Amaranthus palmeri*) control in postharvest wheat stubble in the Central Great Plains. *Weed Technology* 35(6):945–949. DOI: 10.1017/wet.2021.64.

Maity A, Young B, Schwartz-Lazaro LM, Korres NE, Walsh MJ, Norsworthy JK, Bagavathiannan M. 2022. Seedbank management through an integration of harvest-time and post-harvest tactics for Italian ryegrass (Lolium perenne ssp. multiflorum) in wheat. *Weed Technology* 36(2):187–196. doi:10.1017/wet.2022.16

Mao H, Jiang C, Tang C, Nie X, Du L, Liu Y, Wang X. 2023. Wheat adaptation to environmental stresses under climate change: molecular basis and genetic improvement. *Mol Plant* 16(10):1564–1589.

Mendiburu F, Yaseen M. 2020. Agricolae: statistical procedures for agricultural research. Available at: https://myaseen208.github.io/agricolae/, https://cran.r-project.org/package=agricolae.

Meyers SL, Jennings KM, Monks DW, Ballington JR, Jordan DL. 2016. Weed control in southern highbush blueberry with S-metolachlor, flumioxazin, and hexazinone. *Int J Fruit Sci* 16:150–158.

Morsy AS, Mohamed E, Farag S, Tantawy M. 2020. Effects of irrigation regimes and duration of weed interference on grain yield of wheat (Triticum aestivum L.) in Middle Egypt. *Egypt J Agron* 42(3):321–337. doi:10.21608/agro.2020.32917.1217

Osipitan OA, Dille JA, Assefa Y, Knezevic SZ. 2018. Cover crop for early season weed suppression in crops: Systematic review and meta-analysis. *Agronomy Journal* 110:2211–2221. https://doi.org/10.2134/agronj2017.12.0752.

Peairs FB, Bean B, Gossen BD. 2005. Pest management implications of reduced fallow periods in dryland cropping systems in the Great Plains. *Agron J* 97:373–377. doi:10.2134/agronj2005.0373.

Reddy KN, Bryson CT, Nandula VK. 2015. Late-season grass weed management with in-crop and post-harvest herbicides in twin-row glyphosate-resistant soybean. *Am J Plant Sci* 6:213–218. doi:10.4236/ajps.2015.61024.

Ritz C, Baty F, Streibig JC, Gerhard D. 2015. Dose–response analysis using R. PLoS One 10
Roncatto E, Barroso AA, Albrecht AJ, Novello BD, Silva RG, Backes CB. 2023. Shortening critical period of weed control at soybean by residual herbicide mixtures. *Adv Weed Sci* 41. https://doi.org/10.51694/AdvWeedSci/2023;41:00009

Roncatto E, Barroso AA, Albrecht AJ, Novello BD, Silva RG, Backes CB. 2023. Shortening critical period of weed control at soybean by residual herbicide mixtures. *Adv Weed Sci* 41. DOI: 10.51694/AdvWeedSci/2023;41:00009.

RStudio Team. 2024. RStudio: integrated development environment for R. RStudio, PBC. Available at: http://www.rstudio.com/.

Schwartz-Lazaro LM, Copes JT. 2019. A review of the soil seedbank from a weed scientists perspective. *Agronomy* 9: 369. https://doi.org/10.3390/agronomy9070369

Shahzad M, Farooq M, Jabran K, Yasir TA, Hussain M. 2016. Influence of various tillage practices on soil physical properties and wheat performance in different wheat-based cropping systems. *Int J Agri Biol* doi:15.0178.

Shahzad M, Jabran K, Hussain M, Raza MAS, Wijaya L, El-Sheikh MA, Alyemeni MN. 2021. The impact of different weed management strategies on weed flora of wheat-based cropping systems. *PLoS One* e0247137.

Skuodienė R, Matyžiūtė V, Šiaudinis G. 2024. Soil seed banks and their relation to soil properties in hilly landscapes. *Plants* 13: 104. https://doi.org/10.3390/plants13010104

Tørresen KS, Skuterud R, Tandsæther HJ, Breddesen Hagemo M. 2003. Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop Protection* 22:185–200.

Türkseven SG, Uludağ A, Demirci M, Serim AT. 2022. Herbicide resistance in *Avena sterilis* subsp. *ludoviciana* populations from the wheat fields of Turkey. *Turkish Journal of Agriculture and Forestry* 46(6):888–897.

Ulusoy AN, Osipitan OA, Scott J, Jhala AJ, Lawrence NC, Knezevic SZ. 2021. PRE herbicides influence critical time of weed removal in glyphosate-resistant corn. *Weed Technology* 35(2):271–278. doi:10.1017/wet.2020.105

Ulusoy AN, Osipitan OA, Scott J, Jhala AJ, Lawrence NC, Knezevic SZ. 2021. PRE herbicides influence critical time of weed removal in glyphosate-resistant corn. *Weed Technology* 35(2):271–278. DOI: 10.1017/wet.2020.105.

Wang L, Sun X, Peng Y, Chen K, Wu S, Guo Y, Zhang J, Yang H, Jin T, Wu L, et al. 2022. Genomic insights into the origin, adaptive evolution, and herbicide resistance of *Leptochloa chinensis*, a devastating tetraploid weedy grass in rice fields. *Mol Plant* 15:1045–1058. doi:10.1016/j.molp.2022.05.001.

Webster TM, Cardina J, Loux MM. 1998. The influence of weed management in wheat (Triticum aestivum) stubble on weed control in corn (Zea mays). *Weed Technology* 12(3):522–526. doi:10.1017/S0890037X00044249

Williams MM, Ransom CV, Thompson WM. 2007. Volunteer potato density influences critical time of weed removal in bulb onion. *Weed Technology* 21(1):136–140. doi:10.1614/WT-06-009.1

Wilson RG, Miller SD, Westra P, et al. 2007. Glyphosate-induced weed shifts in glyphosate-resistant corn or a rotation of glyphosate-resistant corn, sugarbeet, and spring wheat. *Weed Technology* 21(4):900–909. doi:10.1614/WT-06-199.1.

Young FL, Gealy DR. 1986. Control of Russian Thistle (*Salsola iberica*) with Chlorsulfuron in a wheat (*Triticum aestivum*) summer-fallow rotation. *Weed Science* 34(2):318–324. DOI: 10.1017/S0043174500066893.

Young FL, Thorne ME. 2004. Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. *Crop Protection* 23:1097–1110.

Figure 1

Figure 1. Experimental area, parcel locations, and treatments at Kazova

A: Experimental field, B: Post-harvest glyphosate treatment, C: Post-emergence tribenuron-methyl application, D: Separation of weed seeds from

Figure 2

Figure 2. Wheat yield response to treatments from 2020 to 2022

(T1: PHG+Post-em Tribenuron; T2: PHG+Weedy check; T3: No PHG+Post-em tribenuron; T4: No PHG+Weedy check, T5: PHG+Hand weeding, T6: No: PHG+Hand weeding). * The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($p < 0.05$).

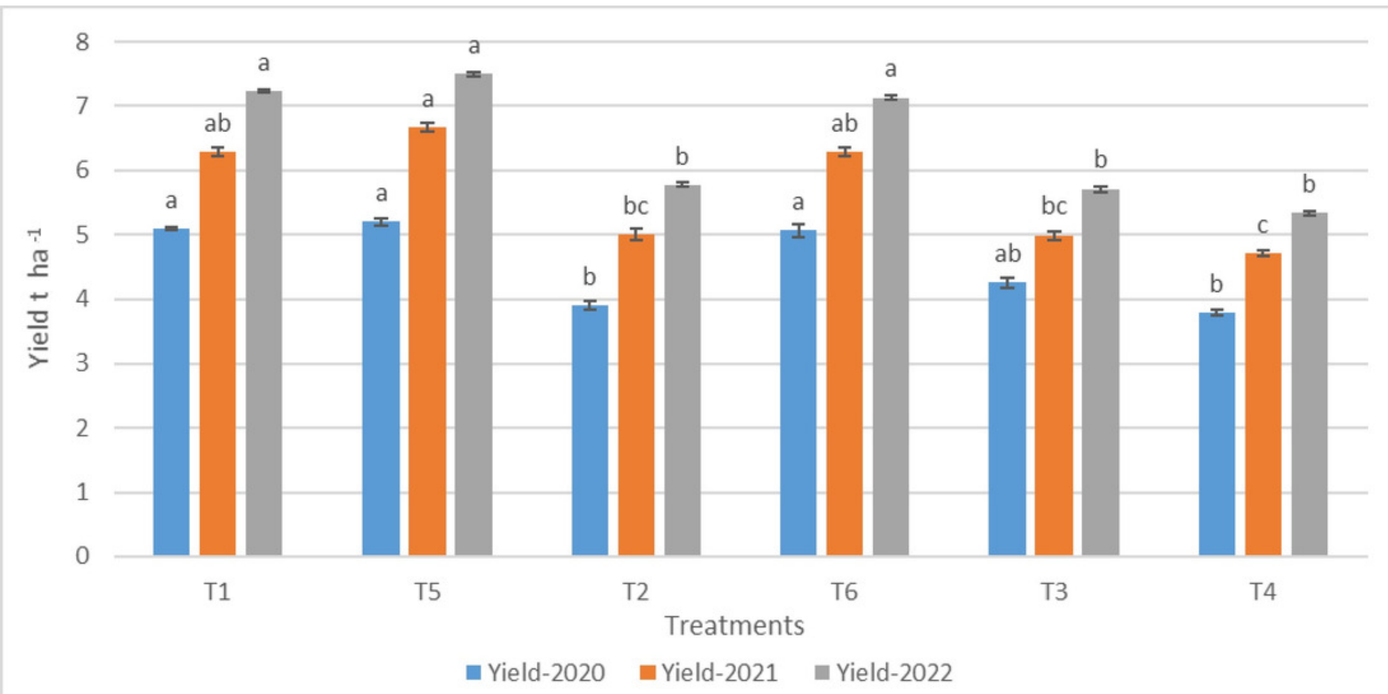

Figure 3

Figure 3. Winter wheat yield (kg ha^{-1}) in response to increasing duration of weed interference as represented by growing degree days (GDD) after wheat emergence for no PHG and PHG applications at Kazova in 2021-23.

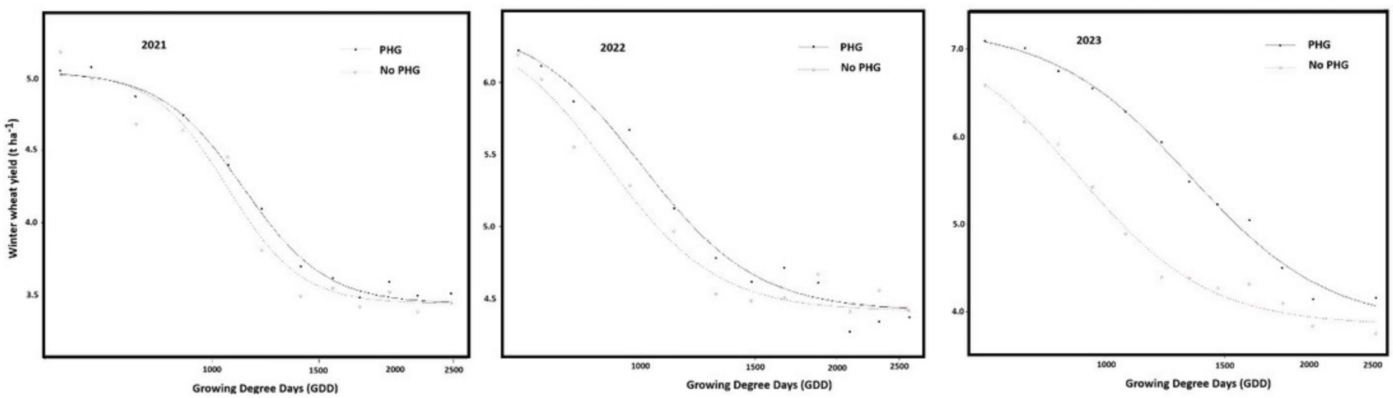

Table 1(on next page)

Table 1. Climate data of experimental fields from 2020-23 and long-term (MGM, 2024)

Table 1. Climate data of experimental fields from 2020-23 and long-term (MGM, 2024)

Month	Average Temperature (˚C)				Cumulative Rainfall (mm)				Long-term (1929-2023)	
	2020	**2021**	**2022**	**2023**	**2020**	**2021**	**2022**	**2023**	**Temperature (˚C)**	**Cumulative rainfall (mm)**
January	3.0	5.0	1	2.6	52.8	62.7	43.3	5.8	1.9	40.9
February	4.0	5.2	4.7	2.2	66.2	8.7	25.9	32.8	3.5	33.8
March	9.8	6.0	3	9.0	32.9	71.2	48.9	35.0	7.4	40.8
April	11.1	13.7	14.5	12.2	22.0	14.2	33.2	114.5	12.5	54.2
May	17.0	18.5	15.2	15.4	35.9	54.6	32.6	61.0	16.5	58.9
June	20.7	20.0	20.7	20.0	81.6	55.5	55.1	71.8	19.9	38.2
July	24.2	24.1	20.7	21.7	1.4	27.7	-	35.6	22.3	11.2
August	22.3	23.6	24.9	24	1.1	17.9	4.7	4.3	22.4	5.6
September	23.0	17.8	19.4	18.9	1.0	27.1	27.4	14.3	18.8	17.7
October	18.0	13.0	13.3	13.7	0.1	10.5	35.3	4.1	13.7	39.3
November	7.4	15.2	9.3	-	11.1	0.1	31.3	-	7.9	44.0
December	5.5	-0.1	6.1	-	17.2	13.0	17.5	-	3.8	47.1
Total/Average	**13.8**	**13.5**	**12.7**	**14.0**	**646.6**	**726.4**	**355.2**	**379.2**	**12.6**	**431.7**

Table 2(on next page)

Table 2. Impact of post-harvest glyphosate with and without post emergence tribenuron-methyl applied on weed density during 2021-2023 (Plant m^{-2})

VERHE: *Veronica hederifola* L.; XANST: *Xanthium strumarium* L.; CIRAR: *Cirsium arvense (*L.*) Scop.*; CONAR: *Convolvulus arvensis* L.; CHEAL: *Chenopodium album* L.; FUMOF: *Fumaria officinalis* L.; GALAP: *Galium aparine* L.; SINAR: *Sinapis arvensis* L.; POLAV: *Polygonum aviculare* L.; POROL: *Portulaca oleracea* L.; LACSE: *Lactuca serriola* L.; SOLNI: *Solanum nigrum* L.; SETVI: *Seteria viridis* L.; AMARE: *Amaranthus retroflexus* L; ALOMY: *Alopecurus myosoroides* Huds. T1: PHG+Post-em Tribenuron; T2: PHG+weedy control; T3: Post-em tribenuron; T4: weedy control

Table 3. Impact of post-harvest glyphosate with and without post emergence tribenuron-methyl applied on weed density during 2021-2023 (Plant m^{-2})

Weed species	**2021**				**2022**				**2023**			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
VERHE	7.0	11.5	15.0	12.5	2.5	9.5	12.3	8.5	1.3	10.3	15.0	14.3
XANST	2.0	0.5	2.5	1.0	3.5	2.5	3.5	2.00	1.5	0.5	3.5	3.8
CIRAR	-	2.0	1.5	5.5	-	3.0	0.3	3.3	-	3.0	0.5	2.8
CONAR	4.0	4.3	6.3	5.5	3.0	1.5	7.5	6.0	1.5	2.8	5.0	7.3
CHEAL	16.0	12.0	8.0	8.3	15.5	13.8	11.3	6.5	7.3	14.0	8.8	4.5
FUMOF	-	1.5	3.0	1.0	-	2.8	2.0	4.0	-	6.8	1.5	3.8
GALAP	-	3.5	1.0	-	-	2.8	-	2.0	-	7.5	-	3.0
SINAR	-	-	1.5	2.5	-	1.5	0.3	3.0	-	2.5	1.3	4.3
POLAV	-	-	-	-	-	1	-	2	-	2.0	-	3.0
POROL	-	-	-	-	-		1.5	2.3	-	-	1.00	3.0
LACSE	-	-	-	-	-	2.3	-	1	-	3.5	0.50	3.0
SOLNI	-	-	-	0.5	-	-	-	-	-	-	-	-
SETVI	1.5	0.5	-	3.0	-	1.0	1.0	3.0	-	3.8	0.8	1.5
AMARE	6.5	4.0	10.3	8.0	2.5	5.0	11.5	9.0	2.5	6.8	14.3	10.5
ALOMY	-	-	-	-	7.5	3.0	1.25	4.3	1.8	2.8	2	3.0
Total	**37.0**	**39.8**	**49.1**	**47.8**	**34.5**	**49.7**	**52.5**	**56.9**	**15.9**	**66.3**	**54.2**	**67.8**
Average Weed Density	**6.2**	**4.4**	**5.5**	**4.8**	**5.8**	**3.8**	**4.8**	**4.1**	**2.7**	**5.1**	**4.5**	**4.8**

VERHE: *Veronica hederifola* L.; XANST: *Xanthium strumarium* L.; CIRAR: *Cirsium arvense (*L.*) Scop.*; CONAR: *Convolvulus arvensis* L.; CHEAL: *Chenopodium album* L.; FUMOF: *Fumaria officinalis* L.; GALAP: *Galium aparine* L.; SINAR: *Sinapis arvensis* L.; POLAV: *Polygonum aviculare* L.; POROL: *Portulaca oleracea* L.; LACSE: *Lactuca serriola* L.; SOLNI: *Solanum nigrum* L.; SETVI: *Seteria viridis* L.; AMARE: *Amaranthus retroflexus* L; ALOMY: *Alopecurus myosoroides* Huds. T1: PHG+Post-em Tribenuron; T2: PHG+weedy control; T3: Post-em tribenuron; T4: weedy control

Table 3(on next page)

Table 3. Average weed seed density (Standard error) at 10 cm soil depth in herbicide treated and control plots before sowing winter wheat

* The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($p < 0.05$).

Table 3. Average weed seed density (Standard error) at 10 cm soil depth in herbicide treated and control plots before sowing winter wheat

Treatment	2021	2022	2023
PHG+post-em tribenuron-methyl	9.8 (2.1) a*	12.9 (0.5) ab	5.3 (1.2) b
PHG+ weedy check	5.4 (0.8) a	7.8 (2.1) b	14.9 (2.3) ab
PHG+ hand weeding	13.7 (3.3) a	8.8 (2.8) b	7.7 (1.4) b
No PHG+Post-em tribenuron-methyl	13.3 (2.7) a	17.4 (2.0) a	22.2 (3.9) a
No PHG+weedy check	8.2 (2.4) a	18.4 (2.0) a	24 (8.1) a
No PHG+hand weeding	12.5 (1.3) a	17 (2.3) a	24.7 (4.5) a

* The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($p < 0.05$).

Table 4 (on next page)

Table 4. Regression parameters (Standard error) and estimation of CTWR (±SE) for No PHG and PHG applications at Kazova in 2021-23.

PHG: Post harvest glyphosate; B: Slope; C: lower limit; D: Upper limit; I_{50}: the GDD at the inflection point; GDD: growing degree days; DAE: Days after emergence

Table 4. Regression parameters (Standard error) and estimation of CTWR (±SE) for No PHG and PHG applications at Kazova in 2021-23.

Year	Treatment	B	C	D	I_{50}	GDD	DAE
2021	No PHG	7.2 (2.7)	3.40 (0.07)	5.02 (0.13)	10.73 (0.50)	711.9 (131.8)	31.47 (7.1)
	PHG	6.8 (1.1)	3.48 (0.04)	5.05 (0.06)	11.1 (0.26)	718.5 (55.3)	31.1 (2.8)
2022	No PHG	4.5 (1.3)	4.44 (0.06)	6.85 (0.74)	7.99 (1.24)	416 (140.6)	16.6 (3.0)
	PHG	4.3 (1.1)	4.32 (0.09)	6.47 (0.25)	10.22 (0.63)	516.5 (112.9)	22.3 (2.8)
2023	No PHG	4.2 (0.5)	3.82 (0.14)	7.25 (0.12)	13.38 (0.33)	465.6 (92.2)	14.5 (2.2)
	PHG	4.4 (0.9)	3.84 (0.10)	7.30 (0.48)	9.05 (0.59)	661.2 (55.8)	31.6 (2.8)

PHG: Post harvest glyphosate; B: Slope; C: lower limit; D: Upper limit; I_{50}: the GDD at the inflection point; GDD: growing degree days; DAE: Days after emergence