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Assessing Herbicide Efficacy and Susceptibility for Weed Management and Enhancing Production of Non-GMO Soybean Cultivation

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Abstract: Soybean (*Glycine max* L.) is a vital leguminous crop known for its rich nutritional profile, including high protein and oil content, making it a valuable resource in global agriculture and human nutrition. In Pakistan due to regulatory issues non-GMO soybean is grown therefore, the universal herbicide control method is not applicable. Similarly, for other crops, specific herbicides are available but for soybean no crop specific herbicide is present. A comprehensive study was conducted over two growing seasons, in 2022 and 2023, at Agronomic Research Farm University of Agriculture Faisalabad. The research involved 16 different treatments, including both six pre-emergence and eight post-emergence herbicides as well as a control group and weedy check. Findings of this study showed that critical importance of weed management in soybean cultivation, as unchecked weed infestation can lead to substantial yield losses. Among the pre-emergence herbicide S-Metolachlor + Pendimethalin performed best and showed higher plant height (54.33 cm & 53.67 cm), 100 grain weight (11.57 g & 12 g), seed yield plant^{-1} (13.07 g and 12.87 g), lower Susceptibility Index (10%), higher weed control percentage (91.21% & 95.65%) higher weed control efficiency (92.02% & 93.43%), herbicide efficiency index (27.54% & 32.48%) and lower weed index (18.16% & 21.70%) during 2022 and 2023 respectively. However, in post emergence herbicide the Fluizefop-p-butyl is most effective herbicide due to less crop injury 10% Susceptibility Index, higher plant height (42.67 cm & 44 cm), whole plant weight (93.33 g & 95 g), 100-grain weight (11.40 g & 11.77 g), seed yield plant^{-1} (12.87 g & 13.13 g), higher weed control percentage (91.12% & 91.03%) higher weed control efficiency (89.73% & 92.36%, herbicide efficiency index (21.18% & 30.41%) and lower weed index (19.42% & 20.08%) in both 2022 and 2023 respectively. Notably, herbicides such as S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium and Mesotrione + Atrazine led to complete plant mortality, resulting lethal to soybean. The findings of this study support the hypothesis that screened the best suitable herbicides with less plant injury, and higher efficiency index. So, it is recommended that the application of S-Metolachlor + Pendimethalin as PRE and Fluizefop-p-butyl as POST showed the least injury and best weed control results with higher grain yield.

Keywords: susceptibility index; soybean; weed management; herbicides; crop yield; agriculture; Pakistan

1. Introduction

Soybean is an imperative leguminous crop which has high nutritional value, it comprises of about 18-22% oil and 40-42% protein. Additionally, it contains a good number of vitamins and carbohydrates [1–4]. Soybean play an important role as medicinal plant, its derivatives are used for many treatments of disease, such as Genistein (an isoflayone phytonutrient in soybean) is used for the prevention of cancer [5]. In soybean, weeds cause more yield reduction than any other abiotic and biotic stresses, they compete for light, space, essential nutrients and soil moisture and also serve as alternate host and provide shelter to many pests, insects, nematodes and pathogens which cause various plant diseases and leads to reduction in soybean yield and increase cost of production [6–9]. Yield reduction in soybean due to weed infestation depends on weed species, density, type and time

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of emergence [10,11]. In major soybean producing countries, weeds are controlled by using herbicides because the cultivars are herbicide resistant. In Pakistan due to regulatory issues non-GMO soybean is grown therefore, the universal herbicide control method is not applicable. Similarly, for other crops, specific herbicides are available but for soybean no crop specific herbicide is present.

For effective weed control in soybean, two hand hoeing are suggested best and resulting increased soybean yield [12]. But due to increase in wage scale and shortage of labor it is very difficult to control weeds manually and it also increase the cost of production up to 40%-60% [13]. Manual weeding is also difficult for progressive farmer to control weeds on large scale farming. So, in this situation chemical weed control is better option to minimize the expenditure and to enhance the soybean yield. In chemical weed control selective herbicide are the good alternative of manual weeding [14–17].

Chemical method for controlling weeds in soybeans is to use herbicide treatments that contain effective PRE- and POST-applied herbicide combinations with various modes of action [18]. When weeds are most competitive in the early part of the season, pre-emergence-applied herbicide can prevent crop yield loss [19–21]. The use of PRE- and POST-applied herbicide premixes has also been shown to have several advantages, particularly in terms of preventing herbicide resistance and ensuring season-long weed control [22–28].

Kumar and Jha [24] carried out an experiment to study effectiveness of different pre and post emergence herbicides labeled for corn, grain, sorghum, soybean and wheat/barley. The results showed that Acetochlor, atrazine, metolachlor, atrazine, mesotrione and sulfentrazone applied as pre-emergence which control the 91% weeds at twelve weeks after treatment. Whereas metribuzin, linuron and pyroxisulfuron with atrazine PRE provide 82% weed control at 12 Week after treatment. On the other hand, acetoclore + flumetsulam control 23% at 12 weeks after treatment. Behera et al. [29] reported that Pendimethalin pre-emergence application provided efficient control of all species from the earliest stages. Furthermore, the second flush of weeds was prevented from emerging by HW and a post-emergence treatment of chlorimuron ethyl at 15 DAS. When soybeans were in their early stage or second flush, the weeds were difficult to suppress with pendimethalin or chlorimuron-ethyl applications alone. Priess et al. [30] check the injury cause by herbicide on soybean canopy formation and yield. The treatment consisted of herbicides were Fomesafen, acifluorfen, S-metolachlor, fomesafen, and S-metolachlor, fomesafen, chlorimuron alone and with glufosinate combination at V2 growth stage. The soybean injury ranged from 9% to 25% at 2nd week and injury level increased to 80% by delay to 6 days. The continuous use of these herbicides in soybeans may be problematic in addition to the possibility of resistance evolving since crop damage regularly following their application [31]. Fornazza et al. [32] conducted an experiment for the selectivity of herbicide for soybean crop contains four pre-emergence herbicides (S-metolachlor, diclosulam, sulfentrazone, and no herbicide application) and seven post emergence herbicides (lactofen, chlorimuron-ethyl, bentazon, lactofen + chlorimuron-ethyl, glyphosate, two sequential glyphosate applications, and no herbicide application). The early-maturing soybean cultivars tested were sensitive to the applied herbicides. The frequency of plant injuries increased when pre- and post-emergence herbicides were used together. Among pre-emergence herbicides, diclosulam and sulfentrazone were the least selective.

Akter et al. [33] comparing chemical weed control to hand weeding, it was found that soybean yield was statistically comparable but due to labor shortage and higher cost it is not economical. There is a long list of herbicides that can be advised for soybean weed management. Some of those are sold in Pakistani marketplaces. A pre-emergence herbicide that inhibits cell division is pendimethalin [34]. It leads to the failure of cell division which is caused by the inhibition of tubulin synthesis and the stop of microtubule structure [35]. Additionally, oxyfluorfen is a photosynthetic inhibitor that inhibits noncyclic electron transport and phosphorylation via photosystem [36]. Acetochlor, also known as N (ethoxymethyl)-2-chloro-6-methylacetanilide, is a cell division inhibitor that inhibits the creation of proteins [37]. Herbicide called halosulfuron, which inhibits acetolactate synthase, is an amino acid inhibitor. an enzyme with complicated branched chain amino acid production [38]. The S-metolachlor is a cell division inhibitor [39]. The half-life of metolachlor, an achloroacetamide, is 23 days [40]. Quizalofop-p-ethyl, aryloxyphenoxy, acetyl CoA carboxylase [34]. Topramezone is a recently developed herbicide that belongs to the pyrazole class and is utilized for the control of both grasses and broadleaf weeds. It prevents homogentisate's structure most likely by inhibiting 4 [hydroxyphenylpyruvate dioxygenase (HPPD)] [41]. Additionally, it causes oxidative stress, damages the photosynthetic system, and increases the permeability of cell membranes [42].

In the context of soybean crop, post-emergence herbicides that target PROTOX, ALS, and EPSPs enzymes are widely employed. However, the application of these herbicides can have an impact on the growth and yield of soybean plants, potentially resulting in leaf injuries characterized by symptoms such as chlorosis and necrosis. This phenomenon is often attributed to the action of post-emergence inhibitors targeting PROTOX and ALS enzymes [43–45]. The genotype sensitivity of the soybean may be tested by early detection of herbicide stress. In order to reduce crop damage, it might also be helpful to evaluate the management methods, soil, and weather conditions by alter the herbicide dose, or choose the right herbicide for the situation. Herbicide injury to crops is often estimated traditionally through visual inspections [46–49].

Prachand et al. [50] reported that good soybean weed control involve using combination with one another to create an integrated weed management strategy for effective soybean weed control. However, the economics and profitability of soybean farming are somewhat disturbed when you consider the current labor shortage and their increased wages for cultural and mechanical weed control. Therefore, it is important to modify chemical weed management methods to address the issues of low labor availability and their high wages. Whereas, soybean plants are very sensitive to herbicide application. Therefore, it has become critical to choose the best herbicide for effective weed management in soybeans with little plant injury. The experiment was conducted to screen herbicides for the best weed control in soybean to obtain its greater seed production in light of the above factors.

2. Materials and Methods

The study was conducted to evaluate the efficacy of various herbicides of different classes and mode of action on soybean (*Glycine max* L.) in pot experiment during 2022 and 2023 in Agronomic Research Area, Department of Agronomy, University of Agriculture Faisalabad, has Latitude: 31.4504° N, Longitude: 73.1350 E, Altitude: 186.4 m [51]. The experiment consisted of 16 treatments, including one control treatment and one weedy check, along with 14 different herbicide treatments containing six pre-emergence herbicides and 8 post emergence herbicides under completely randomized design. Each treatment was replicated three times to ensure robust statistical analysis. Treatments contains Manual Control, Weedy check, S-Metolachlor + Pendimethalin as PRE, Pendimethalin as PRE, S-Metolachlor as PRE, Pendimethalin + Acetochlor as PRE, S-Metolachlor + Atrazine as PRE, Acetochlor + Atrazine as PRE, S-Metolachlor + Atrazine + Mesotrione as POST, Topramezone as POST, Halosulfuron-methyl as POST, Haloxyfop-p-ethyl as POST, Fluizefop-p-butyl as POST, Oxyfluorfen as POST, Mesosulfuron-methyl + Iodosulfuron-methyl sodium as POST, Mesotrione + Atrazine as POST. Standard pots were chosen as the primary containers for this experiment. The selection was based on their suitability for maintaining consistent growing conditions and facilitating thorough observations. Each pot served as an individual experimental unit, allowing for precise monitoring and data collection. To establish a consistent growth medium, a uniform potting mix was prepared and used to fill each pot. The potting mix consisted of a combination of soil, peat moss, and perlite in a 2:1:1 ratio by volume. The soil was air-dried and sieved to remove debris. The peat moss provided organic matter and improved water retention, while perlite enhanced aeration and drainage. The components were thoroughly mixed to ensure uniformity before being added to the pots. This potting mix was carefully formulated to provide optimal conditions for soybean growth while allowing for effective herbicide application and weed establishment. A balanced NPK fertilizer solution was applied to each pot at a rate of 25:50:50 (N: P: K) kg ha^{-1}, ensuring that the soybean plants received adequate nutrition. The fertilizer was applied in two splits: half at the time of sowing and the remaining half 30 days after germination. To protect the soil born disease, seed was treated before planting with Benlate and Tecto @ 1.5-2 grams per 1 kg seed. The application of a fungicides Dithane M-45 with no toxicity to Rhizobia should be used at a

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rate of 4 g per liter of water, sprayed twice during the growing period to prevent fungal diseases. The pots were irrigated regularly to maintain optimal soil moisture conditions. A drip irrigation system was employed to ensure uniform water distribution, with irrigation frequency adjusted based on weather conditions and soil moisture levels. The soil moisture was maintained at approximately 70% of field capacity throughout the growing period.

Prior to initiating the main experiment, a germination test was conducted to determine the germination percentage of the selected soybean cultivar. A representative sample of 100 seeds was placed on moistened blotting paper in labeled trays, and the germinated seeds were counted over 15 days. This preliminary test ensured the quality and potential germination rate of the seeds used in the subsequent experiment.

After sowing the soybean seeds, six different pre-emergence herbicides were applied to their respective treatments according to recommended rates and methods. The herbicides were applied uniformly across the pots using calibrated spraying equipment. After 25 days of sowing, eight different post-emergence herbicides were applied to their respective treatments, adhering to recommended application rates and procedures.

2.1. Plant Parameter Measurements

Susceptibility index, which serves as an indicator of plant injury and herbicide response, was determined. The index was measured over a span of 20 days starting from 15^{th} day after Pre-emergence herbicide application. Post-emergence herbicides were applied at 25 days after sowing, with subsequent data collection over a 20-day period after spray. Data was collected based on visual observations and scored on a scale. The degree of soybean plant injury was estimated through visual observation, rated on a scale ranging from 0% (no injury) to 100% (complete plant mortality). Days to flowering were recorded when the first flower appeared on the soybean plants. Other plant parameters, including plant height, whole plant weight, number of pods per plant, number of seeds per pod, number of seeds per plant, 100-grain weight, and seed yield per plant, were measured at the time of harvesting. Along with crop data weed data was also recorded including weed fresh weight and dry weight, weed control percentage and other following standard procedures as follows:

2.2. Weed Control Percentage

The Weed Control Percentage (WCP) is a measure of how effective a weed control treatment is as compared to an untreated (unweeded) control plot. For each treatment (including the manual control and untreated control), record the Initial weed count before Pre and Post emergence herbicide application and then final weed count after herbicide application at the specified time points (15 DAS, 30 DAS and 45 days after Pre and Post emergence herbicides application). The formula used to calculate weed control percentage was:

$$WCP = \frac{Initial\ Weed\ Count\ -\ Weed\ Count\ \ at\ interval}{Initial\ Weed\ Count} X\ 100 \quad (1)$$

Initial weed count represents the weed population before herbicide application. Weed count at interval represents the weed population after herbicide application at those respective time points weed count at 15, 30 and 45 days after spray. The weed control percentage is calculated based on the reduction in weed count after the herbicide application compared to the initial weed count.

2.3. Weed Control Efficiency (WCE)

The Weed Control Efficiency (WCE) measures the reduction in weed dry weight in treated plot over weed dry weight in unweeded check (control). It's also expressed as a percentage. Where: W_C = Weed dry weight in control (unweeded) plot. W_T = Weed dry weight in treated plot.

$$\mathrm{WCE} = \frac{\mathrm{W}_C - \mathrm{W}_\mathrm{T}}{\mathrm{W}_\mathrm{C}} X\ 100 \quad (2)$$

2.4. Weed Index (WI)

The Weed Index (WI) is a way to measure how effective a specific treatment is as compared to a situation with no weeds at all. It helps us understand how much the treatment affects the crop's potential yield. The WI is shown as a percentage of what the yield could be without any weeds. To calculate the WI, we use two values: the yield from a plot without weeds (YWF) and the yield from the treated plot (YT). We use a simple formula to find the WI:

$$\mathrm{WI} = \frac{\mathrm{Y_{WF}} - \mathrm{Y_T}}{\mathrm{Y_{WF}}} \; X \; 100 \qquad (3)$$

This formula helps us see how much the treatment affects the yield compared to a weed-free situation. A higher WI indicates a greater loss due to weeds, showing the impact of weeds on crop productivity. It's a useful measure to understand the efficiency of weed control methods.

2.5. Weed Persistence Index (WPI)

The Weed Persistence Index (WPI) is a measure that helps us understand how effectively a treatment has reduced weed growth over time. To calculate the WPI, we use four values: the weed dry weight in the control (unweeded) plot (W_C), the weed dry weight in the treated plot (W_T), the weed population in the control (unweeded) plot (W_{PC}), and the weed population in the treated plot (W_{PT}). The formula is as follows:

$$\mathrm{WPI} = \frac{\mathrm{W_T}}{\mathrm{W_C}} \; \mathrm{X} \; \frac{\mathrm{W_{PC}}}{\mathrm{W_{pT}}} \qquad (4)$$

2.6. Herbicide Efficiency Index (HEI)

The Herbicide Efficiency Index (HEI) helps us assess the effectiveness of an herbicide treatment in killing weeds while considering its impact on the crop. To calculate the HEI, we use four values: the yield of the treated plot (Y_T), the yield of the control (unweeded) plot (Y_C), the weed dry weight in the control (unweeded) plot (W_C), and the weed dry weight in the treated plot (W_T). The formula is as follows:

$$HEI = \frac{\frac{\mathrm{Y_T - Y_C}}{\mathrm{Y_C}}}{\frac{\mathrm{W_T}}{\mathrm{W_C}}} \qquad (5)$$

2.7. Weed Management Index (WMI)

The Weed Management Index (WMI) is a measure that combines both yield and weed control aspects. It indicates how well a treatment manages weeds while affecting the crop's yield. The formula considers the yield of the treated plot (Y_T), the yield of the control(unweeded) plot (Y_C), the weed dry weight in the control (unweeded) plot (W_C), and the weed dry weight in the treated plot (W_T):

$$\mathrm{WMI} = \frac{\frac{\mathrm{Y_T - Y_C}}{\mathrm{Y_C}}}{\frac{\mathrm{W_C} - \mathrm{W_T}}{\mathrm{W_C}}} \qquad (6)$$

2.8. Agronomic Management Index (AMI)

The Agronomic Management Index (AMI) combines yield and weed control effects, similar to WMI. It also considers the change in weed dry weight in relation to the control plot. These indices provide valuable insights into the effectiveness of herbicide treatments and their impact on both crop yield and weed management strategies. The formula considers the yield of the treated plot (Y_T), the yield of the control(unweeded) plot (Y_C), the weed dry weight in the control (unweeded) plot (W_C), and the weed dry weight in the treated plot (W_T):

$$\mathrm{AMI} = \frac{\frac{Y_T - Y_C}{Y_c} - \frac{W_C - W_T}{W_C}}{\frac{W_C - W_T}{W_C}} \quad (7)$$

Statistical analysis: Data collected from the pot experiment were analyzed using Statistix 8.1 software. Analysis of variance (ANOVA) was employed to assess the effects of various herbicide treatments on soybean growth parameters. Treatment means were compared using the Least Significant Difference (LSD) test at a 5% level of significance ($P \leq 0.05$). To determine the strength and direction of the association between herbicidal effects on plant growth and potential injury. The experimental design's randomization and replication were crucial for the reliability of the statistical tests, ensuring accurate interpretation of the herbicides' impact on soybean development.

3. Results

The results showed that the pre and post-emergence herbicides have statistically significant effect on soybean growth and development. Before the start of experiment, a germination test was conducted to determine the seed germination percentage of soybean in controlled environment first three days no germination was observed. However, fourth day, 34% of the seeds germinated, and this percentage steadily increased to reach maximum of 92% on the tenth day. This progressive increase in germination percentage is consistent with the typical germination pattern of soybean seeds. The high germination percentage observed in this study indicates the viability of the selected soybean cultivar and the favorable conditions provided for germination.

After sowing the maximum germination (96.6% and 100% respectively) was recorded in manual control treatment followed by the weedy check where no herbicide was applied during the both years. Among the pre emergence herbicide, S-Metolachlor + Pendimethalin treatment showed (90% in 2022 and 93% in 2023) germination followed by Pendimethalin (86.6% in 2022 and 90% in 2023) germination, whereas the minimum germination (73.3% in 2022 and 63% 2023) was observed in Pendimethalin + Acetochlor treatment (Figures 1 and 2).

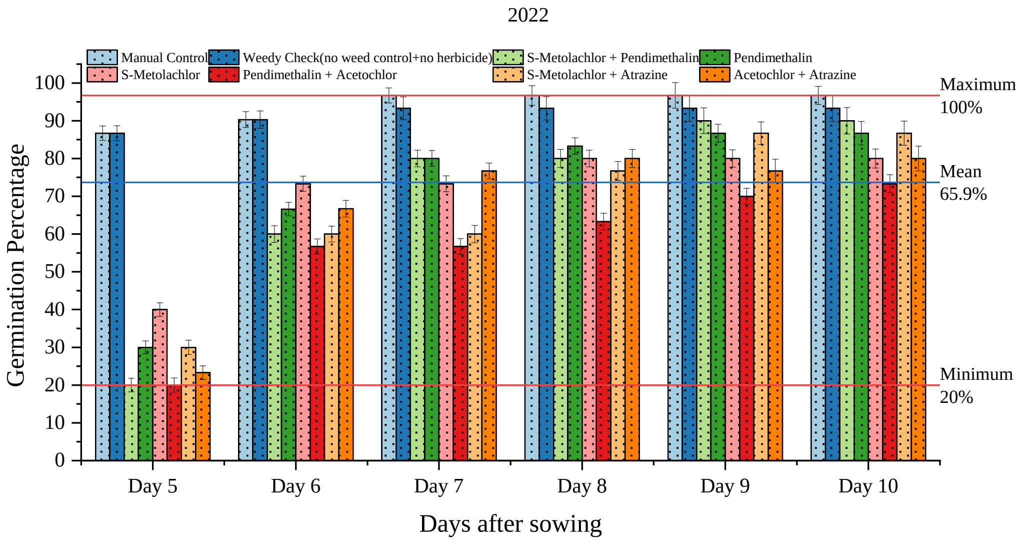

Figure 1. Germination Percentage of Soybean Over Time in Response to Different Pre-Emergence Herbicide Treatments in 2022. This bar graph illustrates the germination percentage (%) of soybean seeds from Day 5 to Day 10 after sowing, under various pre-emergence herbicide. The treatments include Manual Control (weed-free), Weedy Check (weed control absent), and six herbicide formulations: S-Metolachlor; Pendimethalin + Acetochlor; S-Metolachlor + Pendimethalin; Pendimethalin; S-Metolachlor + Atrazine; and Acetochlor + Atrazine.

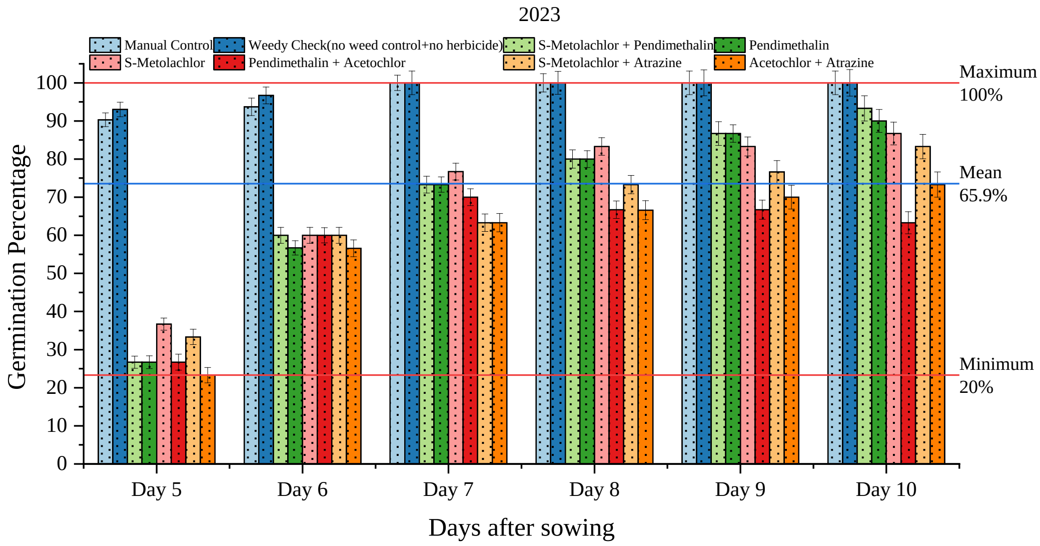

Figure 2. Germination Percentage of Soybean Over Time in Response to Different Pre-Emergence Herbicide Treatments in 2023. This bar chart depicts the percentage of soybean seed germination from Day 5 to Day 10 after sowing under the influence of various pre-emergence. The treatments presented include Manual Control (no weed control), Weedy Check (no herbicide applied), and herbicide treatments such as S-Metolachlor, Pendimethalin + Acetochlor, S-Metolachlor + Pendimethalin, Pendimethalin, S-Metolachlor + Atrazine, and Acetochlor + Atrazine.

The susceptibility index for different herbicide treatments in both the years were calculated and analyzed. Among the Pre-emergence herbicide treatments, Acetochlor + Atrazine (90% and 43% on 2nd and 20th day of herbicide application) and Pendimethalin + Acetochlor (83% and 46% on 2nd and 20th day of herbicide application) showed relatively higher average susceptibility index, indicating their higher injury on soybean plant compared to other herbicides. On the other hand, S-Metolachlor + Atrazine (16%), S-Metolachlor + Pendimethalin, Pendimethalin and S-Metolachlor (10%) showed the same and less plant injury with lower susceptibility index (Figure 3).

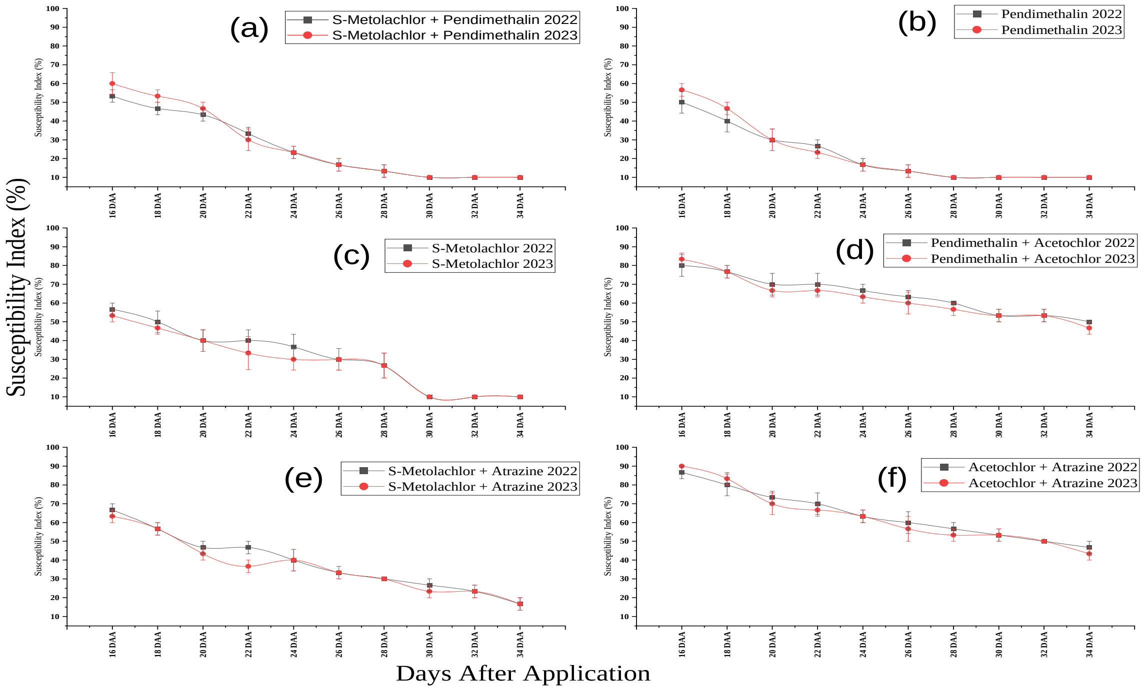

Figure 3. Comparative Analysis of Soybean Susceptibility to Pre-Emergence Herbicides Across Two Consecutive Years. This figure presents a series of line graphs (a-f) depicting the Susceptibility Index

(%) of soybean to different pre-emergence herbicide treatments over a period post-application, comparing results from 2022 and 2023. Each graph represents the change in susceptibility over time for a specific herbicide or combination: (a) S-Metolachlor + Pendimethalin, (b) Pendimethalin, (c) S-Metolachlor, (d) Pendimethalin + Acetochlor, (e) S-Metolachlor + Atrazine, (f) Acetochlor + Atrazine.

In case of post-emergence herbicides, observation made at two days after application revealed that only Oxyfluorfen showed 13% injury while rest of herbicides showed 0% injury. As time progressed the susceptibility index was increased, after the 20 days of application the S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium, Mesotrione + Atrazine showed the susceptibility index more than 90% which mean they almost killed the soybean plant while the Halosulfuron-methyl Oxyfluorfen showed 30% plant injury and the minimal plant injury was reflected in Fluizefop-p-butyl (10%) and Haloxyfop-p-ethyl (10%) herbicide treatment (Figure 4).

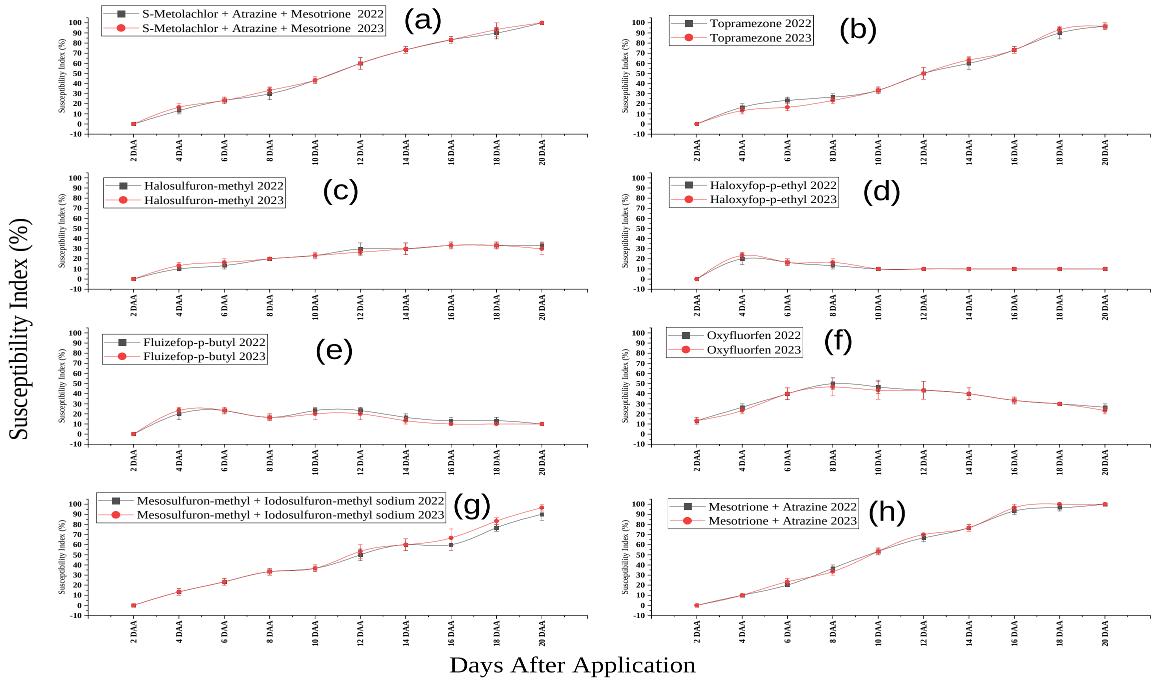

Figure 4. Year-over-Year Comparison of Soybean Susceptibility to Post-Emergence Herbicides. This composite figure contains eight line graphs (a-h), each representing the Susceptibility Index (%) of soybean plants to a specific post-emergence herbicide treatment over time, with comparisons drawn between the years 2022 and 2023. The graphs illustrate the temporal changes in the Susceptibility Index after the application of each herbicide: (a) S-Metolachlor + Atrazine + Mesotrione, (b) Topramezone, (c) Halosulfuron-methyl, (d) Haloxyfop-p-ethyl, (e) Fluazifop-p-butyl, (f) Oxyfluorfen, (g) Mesosulfuron-methyl + Iodosulfuron-methyl sodium, (h) Mesotrione + Atrazine.

The effect of different herbicide treatments on the days to flowering in soybean showed in Table 1. The manual control group exhibited (52.67 and 51 days to flowering in 2022 and 2023 respectively). In comparison weedy check plots resulted a slightly longer time to flowering, with mean values of 54.00-53.33 days in 2022 and 2023. Among the herbicide treatments, S-Metolachlor + Atrazine and Acetochlor + Atrazine demonstrated a relatively shorter time to flowering in both years, with mean values ranging from 57.00 to 59.00 days. In contrast, treatments such as Halosulfuron-methyl and Fluizefop-p-butyl had a slightly longer time to flowering from 56.00 to 59.00 days (Table 1).

Table 1. Effect of pre-emergence and post emergence herbicides on days to flowering, plant height, whole plant weight and seeds per pod of soybean.

Treatments	Days to flowering		Plant height (cm)		Whole Plant weight (g)		Seeds Pod^{-1}	
	2022	2023	2022	2023	2022	2023	2022	2023
Manual Control	52.67±0.33^{e}	51.00±0.58^{g}	52.33±0.44^{a}	54.33±0.44^{a}	119.33±0.88^{a}	121.33±0.88^{a}	3.00±0.00^{a}	3.00±0.00^{a}
Weedy Check(no weed control+no herbicide)	54.00±0.58^{de}	53.33±0.88^{f}	46.33±0.88^{b}	44.17±0.44^{cd}	73.00±1.15^{g}	70.33±1.20^{f}	2.33±0.33^{abc}	2.67±0.33^{a}
S-Metolachlor + Pendimethalin	54.33±0.33^{de}	53.67±0.33^{ef}	45.83±1.36^{bc}	46.50±1.04^{b}	101.33±1.45^{b}	100.67±0.88^{b}	3.00±0.00^{a}	2.67±0.33^{a}
Pendimethalin	55.67±0.88^{cd}	56.00±0.58^{cd}	41.83±0.73^{e}	43.17±0.44^{de}	90.33±0.88^{e}	92.00±1.53^{d}	2.67±0.33^{ab}	2.67±0.33^{a}
S-Metolachlor	56.00±0.58^{cd}	54.67±1.20^{def}	44.17±0.44^{cd}	45.17±1.01^{bc}	98.33±0.88^{c}	99.67±0.88^{b}	2.67±0.33^{ab}	3.00±0.00^{a}
Pendimethalin + Acetochlor	55.00±0.58^{cd}	56.33±0.88^{bcd}	39.00±0.58^{f}	40.33±1.20^{f}	69.67±0.88^{h}	70.33±1.20^{f}	1.67±0.33^{c}	1.67±0.33^{b}
S-Metolachlor + Atrazine	58.67±0.88^{ab}	59.00±0.58^{a}	34.00±0.58^{gh}	32.67±0.33^{i}	64.00±0.58^{j}	61.67±0.88^{h}	2.33±0.33^{abc}	2.67±0.33^{a}
Acetochlor + Atrazine	57.00±0.58^{abc}	57.00±0.58^{bc}	42.90±0.59^{de}	41.23±0.91^{ef}	60.33±0.88^{k}	59.33±0.88^{h}	1.67±0.33^{c}	1.67±0.33^{b}
S-Metolachlor + Atrazine + Mesotrione	-	-	-	-	-	-	-	-
Topramezone	-	-	-	-	-	-	-	-
Halosulfuron-methyl	59.00±0.58^{a}	58.00±0.58^{ab}	32.50±1.04^{h}	31.50±0.76^{i}	67.33±0.88^{i}	65.67±1.20^{g}	2.00±0.00^{bc}	2.33±0.33^{ab}
Haloxyfop-p-ethyl	56.67±0.33^{bc}	56.00±0.58^{cd}	37.90±0.78^{f}	37.17±0.44^{g}	86.33±0.88^{f}	86.00±0.58^{e}	2.67±0.33^{ab}	2.67±0.33^{a}
Fluizefop-p-butyl	56.67±1.76^{bc}	55.33±0.88^{cde}	42.67±1.45^{de}	44.00±0.58^{cd}	93.33±0.88^{d}	95.00±1.15^{c}	3.00±0.00^{a}	3.00±0.00^{a}
Oxyfluorfen	57.00±1.53^{abc}	56.33±0.88^{bcd}	34.80±0.72^{g}	35.17±1.01^{h}	70.00±0.58^{h}	72.00±1.15^{f}	2.67±0.33^{ab}	3.00±0.00^{a}
Mesosulfuron-methyl + Iodosulfuron-methyl sodium	-	-	-	-	-	-	-	-
Mesotrione + Atrazine	-	-	-	-	-	-	-	-
LSD at 5%	2.1605	1.8595	2.1477	1.9337	2.3150	2.6515	0.6790	0.6790

This table elucidates the impact of different pre-emergence and post-emergence herbicide treatments on several critical growth metrics of soybean plants during the years 2022 and 2023. The values are expressed as the mean ± standard deviation, denoted by the letters next to the mean values indicating statistical groupings based on the least significant difference (LSD) test at 5% probability. Absence of data due to complete plant mortality is indicated by dashes. This data is crucial for understanding the temporal effects of herbicide treatments on the developmental stages and overall health of soybean plants.

Among the herbicide treatments the maximum growth and yield attributes were recorded in pre emergence herbicide S-Metolachlor + Pendimethalin which consistently promoted robust soybean growth, resulting in taller plant (45.83 cm in 2022 and 46.50 cm in 2023), higher whole plant weight (101.33 in 2022 and 100.67 g in 2023), seed counts pod^{-1} (3 in 2022 and 2.67 in 2023), number of pods plant^{-1} (41 g in 2022 and 40 in 2023), higher seed production (115 in 2022 and 113.67 2023), 100-grain weight (11.56 g in 2022 and 12 g in 2023), and seed yield plant^{-1}(13.07 g in 2022 and 12.87 g in 2023). Among the post emergence herbicide treatment Fluizefop-p-butyl led to taller Plant (42.67 cm in 2022 and 44 cm in 2023) high plant weights (93.33 g in 2022 and 95 g in 2023), higher seeds pod^{-1} (3 seeds Pod^{-1} in 2022 and 2023), higher pods plant^{-1} (40.33 in 2022 and 42 in 2023), seed production plant^{-1} (113.33 in 2022 and 116.67 in 2023), 100-grain weight (11.40 g in 2022 and 11.77 g in 2023), seed yield plant^{-1} (12.87 g in 2022 and 13.13 g in 2023) indicating potential utility in managing weed competition while promoting soybean growth. Conversely, treatments like Pendimethalin + Acetochlor, Acetochlor + Atrazine, S-Metolachlor + Atrazine resulted in smaller plant height, (39, 42.90, 34 cm in 2022 and 40.33, 41.23, 32.67 cm in 2023 respectively,) lower whole plant weight (69.67, 60.33, 64 g in 2022 and 70.33, 59.43, 61.67 g in 2023 respectively,), seed pod^{-1}(1.67, 1.67, 2.33 in 2022 and 1.67, 1.67, 2.67 in 2023 respectively,), pods plant^{-1} (29.33, 30.67, 34 in 2022 and 30, 29.67, 32.67 in 2023 respectively,), seed plant^{-1} (44.67, 48.33, 76.33 in 2022 and 46.33, 46.67, 76.33 in 2023 respectively,), 100 grain weight (5.53, 5.33, 6.80 g in 2022 and 5.87, 5, 7.10 g in 2023 respectively,) and seed yield plant^{-1} (2.43, 2.40, 5.10g in 2022 and 2.60, 2.10, 5.53 g in 2023 respectively,) suggesting potential negative impacts on soybean reproductive success. While manual weed control treatment resulted in significantly highest values of soybean plant height, whole plant weight, pods plant^{-1}, seeds plant^{-1}, 100 grain weight, and seed yield plant^{-1} as significantly lowest values in weedy check treatment in both years. Notably, herbicides such as S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium and Mesotrione + Atrazine led to complete plant mortality, resulting in no data for growth and yield (Table 2).

Table 2. Comparative Analysis of Herbicide Treatments on Yield Attributes of Soybean.

Treatments	Pods plant^{-1}		Seeds plant^{-1}		100 grain weight		Seed yield plant^{-1} (g)	
	2022	2023	2022	2023	2022	2023	2022	2023
Manual Control	43.00±1.15^{a}	44.00±1.53^{a}	119.33±1.86^{a}	121.67±0.88^{a}	13.35±0.26^{a}	13.91±0.33^{a}	15.97±0.32^{a}	16.43±0.30^{a}
Weedy Check(no weed control+no herbicide)	33.33±0.88^{e}	34.33±1.20^{e}	66.00±0.58^{f}	68.00±1.15^{h}	6.13±0.12^{g}	6.33±0.09^{g}	4.10±0.06^{g}	4.17±0.09^{g}
S-Metolachlor + Pendimethalin	41.00±0.58^{b}	40.00±1.15^{bc}	115.00±0.58^{b}	113.67±0.88^{c}	11.57±0.29^{b}	12.00±0.32^{b}	13.07±0.09^{b}	12.87±0.20^{b}
Pendimethalin	37.00±0.58^{d}	38.33±0.88^{cd}	93.33±1.76^{d}	96.33±1.45^{e}	8.27±0.22^{e}	8.40±0.21^{e}	7.17±0.19e	7.27±0.19^{e}
S-Metolachlor	39.00±0.58^{c}	39.33±0.88^{cd}	103.33±0.88^{c}	105.33±0.88^{d}	10.57±0.35^{c}	10.80±0.30^{c}	10.33±0.12^{c}	10.80±0.06^{c}
Pendimethalin + Acetochlor	29.33±0.88^{g}	30.00±0.58^{f}	44.67±0.88^{i}	46.33±0.88^{j}	5.53±0.23^{gh}	5.87±0.20^{g}	2.43±0.23^{i}	2.60±0.32^{i}
S-Metolachlor + Atrazine	34.00±0.58^{e}	32.67±0.33^{e}	76.33±0.88^{e}	76.33±0.88^{g}	6.80±0.35^{f}	7.10±0.17^{h}	5.10±0.12^{f}	5.33±0.09^{f}
Acetochlor + Atrazine	30.67±0.67^{fg}	29.67±0.88^{f}	48.33±1.76^{h}	46.67±1.45^{j}	5.33±0.15^{h}	5.00±0.06^{f}	2.40±0.12^{i}	2.10±0.12^{j}
S-Metolachlor + Atrazine + Mesotrione	-	-	-	-	-	-	-	-
Topramezone	-	-	-	-	-	-	-	-
Halosulfuron-methyl	32.33±0.88^{ef}	32.00±1.53^{ef}	62.00±1.73^{g}	63.00±1.53^{i}	6.13±0.24^{g}	6.30±0.25^{g}	3.47±0.15^{h}	3.57±0.15^{h}
Haloxyfop-p-ethyl	39.00±0.58^{c}	40.00±0.58^{bc}	100.67±1.45^{c}	103.00±1.53^{d}	9.13±0.15^{d}	9.27±0.19^{d}	8.43±0.23^{d}	8.57±0.20^{d}
Fluizefop-p-butyl	40.33±0.88^{bc}	42.00±0.58^{ab}	113.33±1.20^{b}	116.67±0.88^{b}	11.40±0.32^{b}	11.77±0.37^{b}	12.87±0.19^{b}	13.13±0.26^{b}
Oxyfluorfen	36.00±0.58^{d}	37.00±0.58^{d}	90.00±1.53^{d}	92.33±1.20^{f}	7.90±0.20^{e}	8.03±0.18^{e}	7.13±0.09^{e}	7.20±0.12^{e}

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Mesosulfuron-methyl + Iodosulfuron-methyl sodium	-	-	-	-	-	-	-	-
Mesotrione + Atrazine	-	-	-	-	-	-	-	-
LSD at 5%	1.8902	2.4125	3.3436	2.9105	0.6256	0.6016	0.4323	0.4789

This table presents a detailed comparison of the effects of various pre-emergence and post-emergence herbicide treatments on yield-related parameters of soybean plants over two consecutive years, 2022 and 2023. The parameters include the number of pods per plant, the number of seeds per plant, the weight of 100 grains, and the seed yield per plant (g). Data are expressed as mean ± standard deviation. The subscript letters adjacent to the mean values indicate statistically significant differences where treatments with the same letter are not significantly different based on the Least Significant Difference (LSD) at 5%. Blank cells (indicated by "-") represent conditions where data could not be collected due to complete plant mortality or absence of the treatment in that particular year.

The results from Table 3 on soybean weed management reveal that the application of herbicides significantly influenced weed density and biomass. Chemical treatments such as S-Metolachlor + Pendimethalin and Pendimethalin alone exhibited notable suppression of weed proliferation, with the former reducing weed fresh weight to 5.37 and dry weight to 1.40 in 2022. A combination of S-Metolachlor + Atrazine + Mesotrione significantly lowered weed counts and managed weed biomass effectively, with fresh weights at 30.73 and dry weights at 6.97 in 2022, showing their relative success in mitigating weed competition, The Weedy Check plot, devoid of any herbicide intervention, suffered the highest weed counts, escalating from 19 to 19.67 g in 2022 and from 23.00 to 22.67 in 2023, with the heaviest weed biomass at harvest noted at 81.77 and 89.90 for fresh weight, and 17.53 and 18.77 for dry weight in the respective years (Table 3).

Table 3. Weed Density and Biomass Variation Under Different Herbicide Treatments in Soybean Cultivation.

Treatment	Initial Weed Count		Weed Count at 15 Days after spray		Weed Count at 30 Days after spray		Weed Count at 45 Days after spray		Weeds fresh weight (g) at Harvest		Weeds dry weight (g) at Harvest	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Manual Control	18±0.58^{ab}	21.00±0.58^{b}	0.00±0^{g}	0.00±0^{i}	0.00±0^{f}	0.00±0^{k}	0.00±0.00^{a}	0.00±0^{h}	0.00±0.00^{k}	0.00±0.00^{l}	0.00±0.00^{i}	0.00±0.00^{g}
Weedy Check(no weed control+no herbicide)	19±0.58^{a}	23.00±0.58^{a}	19.67±0.88^{a}	21.00±0.58^{a}	18.67±0.88^{a}	21.67±0.88^{a}	19.67±0.33^{g}	22.67±0.33^{a}	81.77±0.79^{a}	89.90±0.61^{a}	17.53±0.32^{a}	18.77±0.55^{a}
S-Metolachlor + Pendimethalin	0±0	0.00±0	6.67±0.33^{f}	5.33±0.33^{gh}	3.00±0.58^{de}	2.33±0.33^{ij}	1.67±0.33^{f}	1.00±0^{gh}	5.37±0.32^{j}	4.27±0.37^{k}	1.40±0.06^{h}	1.23±0.12^{f}
Pendimethalin	0±0	0.00±0	7.00±0.58^{ef}	7.67±0.33^{ef}	3.67±0.33^{cd}	3.33±0.33^{hij}	2.67±0.33^{ef}	1.67±0.33^{fg}	8.67±0.22^{i}	5.57±0.38^{j}	1.83±0.18^{gh}	1.57±0.29^{f}
S-Metolachlor	0±0	0.00±0	6.33±0.33^{f}	5.00±0.58^{h}	3.33±0.33^{de}	2.00±0.58^{j}	2.00±0.58^{f}	2.00±0.58^{fg}	9.80±0.15^{hi}	7.27±0.19^{i}	1.98±0.17^{g}	1.92±0.12^{ef}
Pendimethalin + Acetochlor	0±0	0.00±0	6.00±0.58^{f}	8.67±0.33^{de}	4.00±0.58^{cd}	5.33±0.88^{ef}	4.00±0.58^{d}	3.00±0.58^{ef}	12.40±0.26^{g}	11.90±0.23^{g}	2.56±0.20^{f}	2.66±0.29^{de}
S-Metolachlor + Atrazine	0±0	0.00±0	5.67±0.33^{f}	5.67±0.33^{gh}	5.00±0.58^{c}	4.0±0.58^{fgh}	4.33±0.33^{d}	3.67±0.33^{e}	13.00±0.17^{g}	13.50±0.29^{f}	2.77±0.09^{f}	3.00±0.31^{d}

Acetochlor + Atrazine	0±0	0.00±0	6.67±0.33^{f}	7.33±0.67^{ef}	4.00±0.58^{cd}	5.67±0.67^{de}	4.00±0.58^{d}	3.00±0.58^{ef}	12.80±0.12^{g}	12.80±0.12^{fg}	2.63±0.05^{f}	2.50±0.06^{de}
S-Metolachlor + Atrazine + Mesotrione	16.67±0.88^{bcd}	17.33±0.88^{ef}	10±0.58^{c}	12.33±0.33^{c}	8.67±0.88^{b}	10.0±0.58^{c}	8.00±0.58^{b}	8.67±0.33^{b}	30.73±0.82^{de}	32.70±0.61^{b}	6.97±0.12^{c}	7.00±0.15^{b}
Topramezone	17.67±0.33^{abc}	16.67±0.33^{f}	9±0.58^{cd}	9.33±0.33^{d}	8.00±0.58^{b}	8.67±0.88^{c}	7.67±0.33^{b}	8.00±0.58^{b}	30.47±0.75^{e}	29.93±0.52^{c}	5.87±0.32^{d}	6.13±0.41^{c}
Halosulfuron-methyl	16.33±0.88^{cd}	17.00±0.58^{ef}	10.00±0.58^{c}	8.67±0.88^{de}	9.00±0.58^{b}	7.0±0.58^{d}	6.00±0.58^{c}	5.33±0.33^{d}	32.00±0.58^{cd}	23.37±0.32^{e}	7.90±0.23^{b}	7.57±0.18^{b}
Haloxyfop-p-ethyl	18.67±0.33^{a}	17.67±0.33^{def}	8.33±0.33^{de}	6.67±0.33^{fg}	4.33±0.33^{cd}	4.33±0.33^{efg}	2.67±0.33^{ef}	2.00±0.58^{fg}	10.63±0.30^{h}	9.83±0.44^{h}	2.93±0.15^{f}	3.03±0.24^{d}
Fluizefop-p-butyl	19±0.58^{a}	18.67±0.33^{cd}	6.33±0.33^{f}	5.33±0.33^{gh}	2.33±0.33^{e}	3.67±0.33^{ghi}	1.67±0.33^{f}	1.67±0.33^{fg}	6.60±0.32^{j}	4.90±0.31^{jk}	1.80±0.17^{gh}	1.43±0.30^{f}
Oxyfluorfen	18.33±0.88^{a}	19.33±0.33^{c}	9.00±0.58^{cd}	8.67±0.88^{de}	5.00±0.58^{c}	5.0±0.58^{efg}	3.33±0.33^{de}	3.00±0.58^{ef}	16.50±0.29^{f}	12.90±0.55^{fg}	4.50±0.23^{e}	2.67±0.20^{de}
Mesosulfuron-methyl + Iodosulfuron-methyl sodium	16±0.58^{d}	17.00±0.58^{ef}	12.33±0.88^{b}	12.00±0.58^{c}	8.67±0.33^{b}	9.33±0.33^{c}	5.67±0.33^{c}	6.00±0.58^{cd}	34.20±0.42^{b}	25.60±0.23^{d}	7.17±0.12^{c}	6.90±0.31^{bc}
Mesotrione + Atrazine	16.33±0.33^{cd}	18.00±0.58^{de}	11.67±0.88^{b}	14.00±0.5^{b}	8.33±0.33^{b}	11.67±0.33^{b}	8.00±0.58^{b}	7.33±0.88^{bc}	32.90±0.49^{c}	32.90±0.49^{b}	7.03±0.24^{c}	7.20±0.25^{b}
LSD at 5%	1.4403	1.2240	1.6103	1.4798	1.4202	1.6281	1.2474	1.3997	1.2815	1.1326	0.5399	0.7781

This table summarizes the effects of various weed control strategies on soybean cultivation, detailing the initial weed count, subsequent weed counts at 15, 30, and 45 days after herbicide application, and the final fresh and dry weed weights at harvest for the years 2022 and 2023. Data are presented as mean values with standard deviations indicated. The subscript letters indicate the statistical significance as determined by the LSD test at the 5% level. The absence of herbicide application is denoted by the Weedy Check treatment, while the Manual Control reflects a weed-free condition achieved through physical removal methods.

Considering the specific Weed Control Percentage (WCP) the Manual Control treatment consistently achieved the highest weed control percentage (WCP) of 100% in both years, representing the most effective weed control method. On the other hand, the Weedy Check treatment, which involved no weed control or herbicide application, consistently had the lowest WCP in both years. The 15-day, 30-day, and 45-day interval results to assess how these herbicide treatments performed in controlling weeds over time. Among the herbicide treatments, S-Metolachlor + Pendimethalin consistently demonstrated effective weed control at all three intervals. It showed a WCP of 64.84%, 76.78% at 15 days, which improved to 84.27%, 89.90% at 30 days and further increased to 91.21%, 95.65% at 45 days in the year 2022 and 2023 respectively. Among the post-emergence Haloxyfop-p-ethyl and Fluizefop-p-butyl herbicides resulted (55.36%, 62.31 in 2022 and 66.70%, 71.44% 2023 respectively) at 15 days which improved 85.77%, 88.56% in 2022 and 2023 and 91.12%, 91.03% in 2022 and 2023 at 45 Days interval. On the other hand, the S-Metolachlor + Atrazine + Mesotrione treatment (49.77%) showed relatively lower weed control (Table 4). When comparing the 15-day, 30-day, and 45-day intervals. Among the herbicide treatments, S-Metolachlor + Pendimethalin, Pendimethalin, S-Metolachlor perform best in pre-emergence while in post-emergence herbicides Haloxyfop-p-ethyl and Fluizefop-p-butyl demonstrated reliable and consistent performance in managing weeds over time. The results for the Weed Persistence Index (WPI) at different application timings (15, 30, and 45

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days after sowing - DAS) showed S-Metolachlor + Pendimethalin, sole Pendimethalin, and sole S-Metolachlor, applied at pre-emergence (PRE), displayed relatively low WPI at 15, 30, and 45 DAS. Topramezone and Fluizefop-p-butyl, applied post-emergence (POST), also demonstrated low WPI, suggesting good weed control. In 2022, Topramezone had a WPI of 0.79 at 45 DAS, while Fluizefop-p-butyl had a WPI of 0.87. In 2023, these values were 0.82 and 0.46, respectively, indicating effective weed suppression. Halosulfuron-methyl showed low WPI in 2022 (1.01 at 45 DAS) but an increase in 2023 (1.26), indicating potential weed resistance or adaptation. Haloxyfop-p-ethyl displayed increasing WPI in both years, with 0.51 at 30 DAS in 2022 and 2.23 at 45 DAS in 2023, indicating reduced efficacy over time (Table 5).

Table 4. Comparative Analysis of Weed Control Efficacy Over Time Across Different Herbicide Treatments in Soybean.

Treatments	Dose ml acre^{-1}	Time of application	Weed Control Percentage at 15 Day after spray		Weed Control Percentage at 30 Day after spray		Weed Control Percentage at 45 Day after spray	
			2022	2023	2022	2023	2022	2023
Manual Control	-	-	100±0^{a}	100±0^{a}	100±0^{a}	100±0^{a}	100.00±0^{a}	100±0^{a}
Weedy Check(no weed control+no herbicide)	-	-	3.88±6.94^{i}	8.45±4.81^{j}	1.30±7.57^{f}	5.81±2.91^{j}	3.70±3.70^{g}	1.26±3.77^{i}
S-Metolachlor + Pendimethalin	900	PRE	64.84±2.11^{bc}	76.78±1.54^{b}	84.27±2.7^{bc}	89.90±1.21^{bc}	91.21±1.79^{ab}	95.65±0.11^{ab}
Pendimethalin	1000	PRE	62.90±4.17^{bc}	66.56±2.18^{de}	80.76±1.3^{bcd}	85.42±1.81^{bcd}	85.94±1.83^{bcd}	92.81±1.33^{abc}
S-Metolachlor	800	PRE	66.61±1.98^{b}	78.17±2.90^{b}	82.43±1.81^{bcd}	91.23±2.69^{b}	89.54±2.83^{bc}	91.42±2.30^{bcd}
Pendimethalin + Acetochlor	1000	PRE	68.45±2.66^{b}	62.27±1.77^{ef}	78.82±3.31^{bcd}	76.90±3.40^{ef}	78.82±3.31^{d}	86.81±2.84^{cd}
S-Metolachlor + Atrazine	800	PRE	70.12±2.03^{b}	75.40±0.99^{bc}	73.45±3.85^{d}	82.53±2.69^{cde}	77.15±1.85^{d}	84.04±1.52^{d}
Acetochlor + Atrazine	800	PRE	64.84±2.11^{bc}	68.20±2.30^{cde}	78.81±3.51^{bcd}	75.20±3.52^{ef}	78.81±3.51^{d}	87.01±2.41^{cd}
S-Metolachlor + Atrazine + Mesotrione	1000	POST	39.76±3.99^{ef}	28.46±4.21^{i}	45.32±6.47^{e}	42.22±2.76^{hi}	51.46±5.81^{f}	49.77±3.01^{h}
Topramezone	30	POST	49.02±3.35^{df}	43.87±3.19^{h}	54.68±3.32^{e}	47.92±5.50^{h}	56.54±2.41^{ef}	51.96±3.53^{gh}
Halosulfuron-methyl	15 g acre^{-1}	POST	38.06±6.74^{fg}	49.14±4.37^{gh}	48.89±1.11^{e}	58.96±2.01^{g}	62.92±4.83^{e}	68.44±3.01^{e}
Haloxyfop-p-ethyl	350	POST	55.36±1.52^{cd}	62.31±1.20^{ef}	76.71±2.24^{cd}	75.49±1.68^{ef}	85.77±1.56^{bcd}	88.56±3.49b^{cd}
Fluizefop-p-butyl	800	POST	66.70±0.99^{b}	71.44±1.57^{bcd}	87.60±2.14^{b}	80.31±1.98^{def}	91.12±1.95^{b}	91.03±1.86b^{cd}
Oxyfluorfen	350	POST	50.50±4.8^{d}	55.00±5.23^{fg}	72.42±3.96^{d}	74.04±3.35^{f}	81.90±0.99^{cd}	84.47±3.05^{d}
Mesosulfuron-methyl + Iodosulfuron-methyl sodium	100	POST	23.10±2.7^{h}	29.48±1.00^{i}	45.83±1.0^{e}	44.98±2.62^{h}	64.36±3.2^{e}	64.50±4.28^{ef}
Mesotrione + Atrazine	1000	POST	28.68±4.43^{gh}	22.27±0.72^{i}	48.90±2.7^{e}	35.05±2.88^{i}	50.98±3.74^{f}	59.48±3.58^{fg}
LSD at 5%			10.582	8.1423	10.081	8.1057	8.7986	8.0249

This table presents the efficacy of various weed control treatments in soybean, measured as the percentage of weed control at 15, 30, and 45 days afterherbicide application for two consecutive years, 2022 and 2023. The treatments are listed alongside the doses applied per hectare and the timing of application (PRE for pre-emergence and POST for post-emergence). Values are mean percentages with standard deviations, and the subscript letters denote statistical significance based on the LSD test at 5%. A value of 100% indicates complete weed control, as observed in the Manual Control treatment, whereas lower percentages indicate less effective weed control.

S-Metolachlor + Pendimethalin herbicide emerged as a strong performer, with a WCE of 92.02% in 2022 and a slight improvement to 93.43% in 2023. Which is statistically at par with sole pendimethalin (89.54% in 2022 and 91.65% in 2023) and sole S-Metolachlor (88.69% in 2022 and 89.79% in 2023). In post emergence herbicides, Fluizefop-p-butyl herbicide treatment excelled in WCE, with values of 89.73% in 2022 and 92.36% in 2023, indicating its remarkable effectiveness in controlling weeds. While Oxyfluorfen achieved a WCE of 74.33% in 2022, it notably improved to 85.79% in 2023. While the lower WCE was exhibited in S-Metolachlor + Atrazine + Mesotrione with WCE of 60.27% in 2022, this treatment showed improvement, reaching 62.70% in 2023. Mesosulfuron-methyl + Iodosulfuron-methyl sodium starting at a WCE of 59.09% in 2022, it increased to 63.23% in 2023. Mesotrione + Atrazine herbicide treatment showed a WCE of 59.89% in 2022, with a slight increase to 61.63% in 2023 (Table 6).

Table 5. Analysis of Weed Control Durability Through the Weed Persistence Index (WPI) in Soybean Over Multiple Intervals.

Treatments	Dose ml acre^{-1}	Time of application	Weed Persistence Index (WPI) at 15 DAS		Weed Persistence Index (WPI) at 30 DAS		Weed Persistence Index (WPI) at 45 DAS	
			2022	2023	2022	2023	2022	2023
Manual Control	-	-	0.00±0.00^{j}	0.00±0.00^{i}	0.00±0.00^{e}	0.00±0.00^{f}	0.00±0.00^{c}	0.00±0.00^{c}
Weedy Check(no weed control+no herbicide)	-	-	1.00±0.05^{a}	1.00±0.05^{a}	1.01±0.06^{a}	1.00±0.05^{ab}	1.00±0.03^{ab}	1.00±0.04^{b}
S-Metolachlor + Pendimethalin	900	PRE	0.24±0.02^{i}	0.26±0.03^{gh}	0.54±0.13^{d}	0.62±0.07^{cde}	1.07±0.31^{ab}	1.49±0.15^{ab}
Pendimethalin	1000	PRE	0.29±0.01^{hi}	0.23±0.04^{h}	0.55±0.10^{d}	0.57±0.14^{cde}	0.80±0.15^{ab}	1.17±0.13^{b}
S-Metolachlor	800	PRE	0.35±0.02^{ghi}	0.43±0.02^{def}	0.64±0.03^{cd}	1.30±0.34^{a}	1.42±0.58^{a}	1.45±0.55^{ab}
Pendimethalin + Acetochlor	1000	PRE	0.49±0.08^{ef}	0.34±0.03^{fgh}	0.71±0.11^{bcd}	0.60±0.09^{cde}	0.74±0.11^{b}	1.14±0.21^{b}
S-Metolachlor + Atrazine	800	PRE	0.55±0.05^{de}	0.60±0.10^{bc}	0.61±0.08^{d}	0.91±0.15^{bc}	0.72±0.04^{b}	0.99±0.07^{b}
Acetochlor + Atrazine	800	PRE	0.44±0.02^{efg}	0.39±0.04^{efg}	0.73±0.10^{bcd}	0.52±0.06^{de}	0.77±0.10^{ab}	1.09±0.22^{b}
S-Metolachlor + Atrazine + Mesotrione	1000	POST	0.79±0.06^{bc}	0.64±0.03^{bc}	0.87±0.09^{abc}	0.81±0.05^{bcd}	0.90±0.03^{ab}	0.98±0.03^{b}
Topramezone	30	POST	0.74±0.06^{bc}	0.74±0.06^{b}	0.79±0.06^{bcd}	0.82±0.04^{bcd}	0.83±0.03^{ab}	0.93±0.01^{b}
Halosulfuron-methyl	15 g acre^{-1}	POST	0.87±0.06^{b}	1.00±0.11^{a}	1.01±0.05^{a}	1.26±0.09^{a}	1.08±0.10^{ab}	1.73±0.12^{ab}
Haloxyfop-p-ethyl	350	POST	0.39±0.01^{fgh}	0.51±0.03^{cde}	0.73±0.07^{bcd}	0.82±0.10^{bcd}	0.77±0.09^{ab}	2.23±0.70^{a}
Fluizefop-p-butyl	800	POST	0.32±0.02^{ghi}	0.30±0.04^{fgh}	0.87±0.17^{abc}	0.46±0.09^{e}	1.26±0.57^{ab}	1.27±0.58^{b}
Oxyfluorfen	350	POST	0.57±0.05^{de}	0.35±0.05^{fgh}	0.99±0.14^{a}	0.64±0.10^{cde}	1.05±0.17^{ab}	1.20±0.33^{b}

Mesosulfuron-methyl + Iodosulfuron-methyl sodium	100	POST	0.66±0.05^{cd}	0.65±0.06^{bc}	0.88±0.03^{abc}	0.86±0.06^{bcd}	0.93±0.03^{ab}	1.40±0.08^{ab}
Mesotrione + Atrazine	1000	POST	0.69±0.08^{cd}	0.58±0.04^{cd}	0.90±0.01^{ab}	0.71±0.02^{bcde}	0.97±0.12^{ab}	1.23±0.18^{b}
LSD at 5%			0.1350	0.1535	0.2584	0.3417	0.6726	0.8584

This table evaluates the longevity of weed control provided by various herbicide treatments in soybeans, using the Weed Persistence Index (WPI) at 15, 30, and 45 days after spraying (DAS). The WPI is a measure of weed presence and density; a WPI of 1 indicates no control, whereas values closer to 0 indicate more effective weed suppression. The table lists herbicide treatments, dosages in ml $acre^{-1}$ or g $acre^{-1}$, and whether the application was pre-emergence (PRE) or post-emergence (POST). The values are the mean WPI scores with standard deviations as error margins, and letters indicate statistical significance determined by the least significant difference (LSD) at 5%.

Herbicide efficiency index (HEI) for the year 2022 and 2023 across all herbicide treatments, S-Metolachlor + Pendimethalin consistently emerged as the most effective pre herbicide, with an impressive HEI of 27.54 in 2022 and an even higher HEI of 32.48 in 2023. While in post Fluizefop-p-butyl, despite a higher HEI value in 2022 (21.18), exhibited a substantial increase in HEI to 30.41 in 2023, signifying its potential for enhancing herbicide efficiency (Table 6).

Table 6. Effect of different weed control treatment on Weed Control Efficiency (WCE), Herbicide Efficiency Index (HEI), Weed Management Index (WMI) and Agronomic Management Index (AMI) in Soybean.

Treatments	**Weed Control Efficiency (%)**		**Herbicide Efficiency Index (HEI)**		**Weed Management Index (WMI)**		**Agronomic management Index (AMI)**	
	2022	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
Manual Control	100±0.00^{a}	100±0.00^{a}	-	-	2.90±0.08^{a}	2.94±0.07^{a}	1.90±0.08^{a}	1.94±0.07^{a}
Weedy Check (no weed control+no herbicide)	-	-	-	-	-	-	-	-
S-Metolachlor + Pendimethalin	92.02±0.33^{b}	93.43±0.64^{b}	27.54±1.40^{a}	32.48±3.66^{a}	2.38±0.02^{a}	2.23±0.05^{abc}	1.38±0.02^{a}	1.23±0.05^{abc}
Pendimethalin	89.54±1.01^{bc}	91.65±1.55^{b}	7.23±0.36^{d}	9.53±1.88^{c}	0.84±0.06^{cd}	0.81±0.05^{def}	-0.16±0.06^{cd}	-0.19±0.05^{def}
S-Metolachlor	88.69±0.99^{c}	89.79±0.62^{bc}	13.65±1.17^{c}	15.70±0.95^{b}	1.72±0.04^{b}	1.77±0.02^{bcd}	0.72±0.04^{b}	0.77±0.02^{bcd}
Pendimethalin + Acetochlor	85.40±1.15^{d}	85.83±1.55^{cd}	-2.83±0.47^{h}	-2.79±0.72^{ef}	-0.48±0.07^{f}	-0.44±0.09^{gh}	-1.48±0.07^{f}	-1.44±0.09^{gh}
S-Metolachlor + Atrazine	84.22±0.50^{d}	84.01±1.63^{d}	1.56±0.22^{ef}	1.76±0.10^{de}	0.29±0.03^{de}	0.33±0.03^{efg}	-0.71±0.03^{de}	-0.67±0.03^{efg}
Acetochlor + Atrazine	85.02±0.27^{d}	86.68±0.31^{cd}	-2.77±0.24^{h}	-3.74±0.29^{f}	-0.49±0.03^{f}	-0.57±0.03^{ghi}	-1.49±0.03^{f}	-1.57±0.03^{ghi}
S-Metolachlor + Atrazine + Mesotrione	60.27±0.69^{g}	62.70±0.81^{f}	-2.52±0.04^{h}	-2.68±0.06^{ef}	-1.66±0.02^{g}	-1.60±0.02^{ij}	-2.66±0.02^{g}	-2.60±0.02^{ij}

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Topramezone	66.54±1.81^{f}	67.32±2.18^{e}	-3.01±0.15^{h}	-3.09±0.20^{ef}	-1.51±0.04^{g}	-1.49±0.05^{hij}	-2.51±0.04^{g}	-2.49±0.05^{hij}
Halosulfuron-methyl	54.94±1.32^{h}	59.68±0.94^{f}	-0.34±0.07^{g}	-0.36±0.09^{ef}	-0.28±0.07^{ef}	-0.24±0.05^{fg}	-1.28±0.07^{ef}	-1.24±0.05^{fg}
Haloxyfop-p-ethyl	83.27±0.83^{d}	83.84±1.28^{d}	6.34±0.35^{d}	6.58±0.41^{cd}	1.27±0.08^{bc}	1.26±0.07^{cde}	0.27±0.08^{bc}	0.26±0.07^{cde}
Fluizefop-p-butyl	89.73±0.99^{bc}	92.36±1.58^{b}	21.18±1.69^{b}	30.41±5.41^{a}	2.39±0.07^{a}	2.33±0.08^{ab}	1.39±0.07^{a}	1.33±0.08^{ab}
Oxyfluorfen	74.33±1.32^{e}	85.79±1.08^{cd}	2.91±0.19^{e}	5.20±0.50^{cd}	1.00±0.03^{c}	0.85±0.03^{de}	0.00±0.03^{c}	-0.15±0.03^{de}
Mesosulfuron-methyl + Iodosulfuron-methyl sodium	59.09±0.68^{g}	63.23±1.63^{ef}	-2.45±0.04^{h}	-2.73±0.12^{ef}	-1.69±0.02^{g}	-1.58±0.04^{ij}	-2.69±0.02^{g}	-2.58±0.04^{ij}
Mesotrione + Atrazine	59.89±1.37^{g}	61.63±1.34^{f}	-2.50±0.08^{h}	-2.61±0.09^{ef}	-1.67±0.04^{g}	-1.62±0.04^{ij}	-2.67±0.04^{g}	-2.62±0.04^{ij}
LSD at 5%	3.0792	4.1463	1.8812	5.0005	0.6225	1.0546	0.6225	1.0546

This table presents a comprehensive comparison of various weed control treatments and their effects on Weed Control Efficiency (WCE), Herbicide Efficiency Index (HEI), Weed Management Index (WMI), and Agronomic Management Index (AMI) for the years 2022 and 2023. The WCE measures the percent reduction in weed growth, the HEI quantifies the effectiveness of the herbicide action, the WMI assesses the overall weed suppression over time, and the AMI evaluates the combined impact of weed control on crop management. Values are presented as means with a letter denoting statistical significance, where the same letters within a column indicate no significant difference. A higher value in WCE and lower in WMI and AMI reflects better performance. The Least Significant Difference (LSD) at 5% is provided for discerning significance among treatment means.

In both 2022 and 2023, the pre-herbicide treatments, S-Metolachlor + Pendimethalin consistently performed well, with highest average WMI values (2.90 in 2022 and 2.94 in 2023) and higher AMI (1.38 in 2022 and 1.23 in 2023). Following closely, Pendimethalin (WMIs of 0.84 in 2022 and 0.81 in 2023) and Metolachlor (WMIs of 1.72 in 2022 and 1.77 in 2023; AMI of 0.72 in 2022 and 0.77 in 2023) demonstrating consistent positive contributions to weed control and good agronomic management. In post emergence herbicides Haloxyfop-p-ethyl and Fluizefop-p-butyl also consistently performed well, with higher WMI (1.27 and 2.39 in 2022, and 1.26 and 2.33 in 2023, respectively) and AMI (0.27 and 1.39 in 2022, 0.26 and 1.33 in 2023, respectively). Manual Control consistently displayed highest WMI (2.90 in 2022 and 2.94 in 2023) and highest AMI values (1.90 in 2022 which increased slightly to 1.94 in 2023), indicating effective weed management capabilities and agronomic management practices. In contrast, several herbicide treatments consistently exhibited negative WMI and AMI values over both 2022 and 2023, including Pendimethalin + Acetochlor, S-Metolachlor + Atrazine, Acetochlor + Atrazine, S-Metolachlor + Atrazine + Mesotrione, Topramezone, Halosulfuron-methyl, Mesosulfuron-methyl + Iodosulfuron-methyl sodium and Mesotrione + Atrazine (Table 6). The Weed Index (WI) graph depicted that S-Metolachlor + Pendimethalin showed lower from 18.16% in 2022 to 21.70% in 2023, Fluizefop-p-butyl also fell into this category, with a WI value of 19.42% in 2022 and 20.08% in 2023 indicating its effectiveness in controlling weeds. Notably, S-Metolachlor + Atrazine displayed moderate weed control capabilities, with a WI value of 68.06% in 2022 and 67.55% in 2023. Halosulfuron-methyl demonstrated similar effectiveness, with a WI of 78.29% in 2022 and 78.30% in 2023. While Acetchlor + Atrazine and Pendimethalin + Acetochlor showed the higher WI, which mean lowest yield with lower weed management. In light of this clarification, it's evident that S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium, and Mesotrione + Atrazine have had damaging effects on soybean growth, as reflected by the Weed Index values of 100.00% in both years (Figure 5).

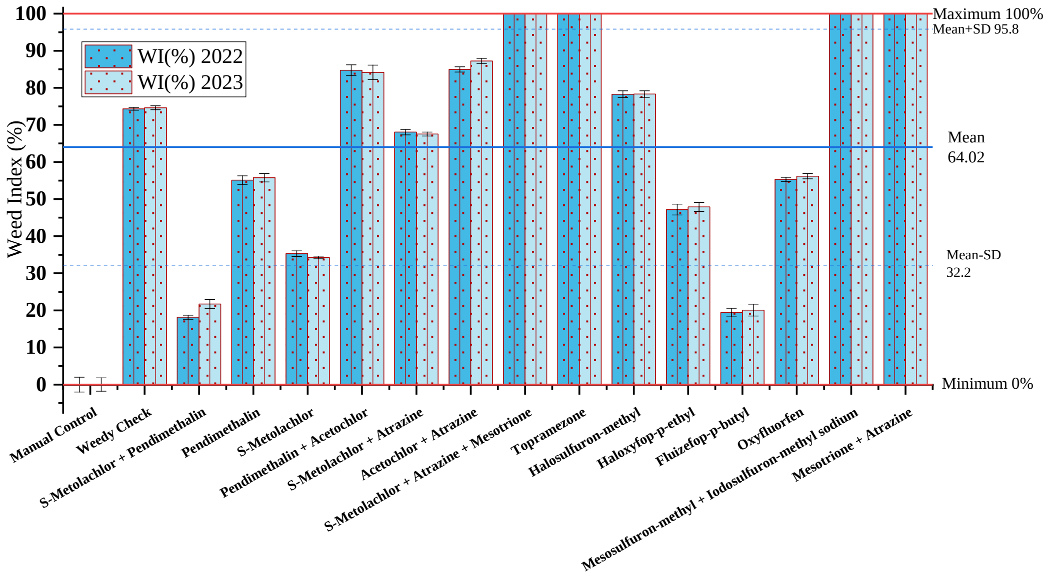

Figure 5. Impact of Weed Control Treatments on Weed Index in Soybean Across Two Years. This bar graph represents the effectiveness of various weed control treatments in soybean as measured by the Weed Index (WI%) for the years 2022 and 2023. The Weed Index quantifies the reduction in yield potential due to weed presence, with higher percentages indicating greater yield loss. Treatments compared include Manual Control, Weedy Check, and various herbicide treatments S-Metolachlor; Pendimethalin + Acetochlor; S-Metolachlor + Atrazine and others.

4. Discussion

The experimental outcomes present insightful revelations into the efficacy of various pre and post-emergence herbicides on the growth and development of soybean. The study's objectives aligned with identifying herbicides that optimize soybean yield, are well-reflected in the findings. The investigation commenced with a germination test, a foundational step in assessing the viability of the soybean cultivar under controlled conditions. The initial absence of germination, followed by a gradual increase to a peak germination of 92% by the tenth day, underscored the typical germination behavior of soybean seeds and established the baseline for the experiment [52].

The impact of pre-emergence herbicides on seed germination was a focal point of the study. Germination data was recorded over a span of 15 days after sowing the soybean seeds to check the effect of Pre-emergence herbicides on soybean seed germination. In both years no germination observed during the initial Four days and progressively increasing germination as time advanced. It was observed that the manual control, which represents the natural soil condition without herbicide intervention, provided the most conducive environment for soybean germination, evidenced by the highest germination percentage by day 10. Notably, the combination of S-Metolachlor and Pendimethalin approached the germination rates of the manual control, suggesting a potential compatibility with soybean emergence. In contrast, combinations involving Pendimethalin with Acetochlor and S-Metolachlor with Atrazine were less conducive to germination, which could be indicative of their phytotoxic effects that align with previous research showed negative impacts of certain herbicide combinations on legume germination [50]. The moderate germination rates in treatments with Pendimethalin and S-Metolachlor alone suggest a degree of selectivity, allowing for soybean emergence despite the presence of these herbicides. The treatment with Acetochlor and Atrazine showed the least favorable outcomes for germination, potentially reflecting a more pronounced inhibitory effect on soybean germination [28].

The pre-emergence herbicide has significant plant injury over two years present a compelling trend in the susceptibility index (SI) of soybean plants to different treatments. The susceptibility index of Pre-emergence herbicides was taken when the plant emerged enough to record data after 16 days after sowing. Initially, at 16 days after application (DAA), there was no injury observed in the Manual Control and Weedy Check, which serves as a baseline for comparison. However, significant plant injury was noted in treatments with S-Metolachlor + Pendimethalin, Pendimethalin, and Acetochlor + Atrazine, with the latter showing the highest SI, especially in 2023. As the days progressed, a general decrease in SI was observed for most treatments by 34 DAA, suggesting a recovery or adaptation of the soybean plants to the initial herbicide stress. Notably, the Manual Control and Weedy Check treatments maintained a consistent SI of zero, underlining their safety in terms of plant injury. The persistent high SI in the Acetochlor + Atrazine treatment indicates a sustained adverse effect, raising concerns about potential long-term impacts on soybean health and development. Conversely, the treatments with S-Metolachlor + Pendimethalin and Pendimethalin Reflected a gradual decline in plant injury over time, hinting at a possible initial phytotoxic response followed by subsequent recovery. The data suggest that while some pre-emergence herbicides can cause initial stress to soybean plants, the degree of impact and the plant's ability to recover varies significantly depending on the herbicide combination used [53]. Whereas the post-application herbicides showed S-Metolachlor + Atrazine + Mesotrione combinations, showing a marked increase in plant injury over time in both years, reaching 100% injury by 20 days after application (DAA). This suggests a potent herbicidal effect leading to complete plant mortality [54]. Topramezone shows a less pronounced yet substantial increase in injury over the same period. In contrast, Halosulfuron-methyl and Haloxyfop-p-ethyl treatments result in a relatively stable injury index post-application, which does not escalate to the same levels, indicating these herbicides are less detrimental to the plants compared to the others. Fluizefop-p-butyl also shows a moderate injury that minimized over time, suggesting some recovery or resistance mechanism in the plants. Oxyfluorfen and Mesosulfuron-methyl + Iodosulfuron-methyl sodium showed gradual increase in injury, but the S-Metolachlor + Atrazine + Mesotrione combination. Mesotrione + Atrazine results in complete plant mortality by 20 DAA, showing its high phytotoxicity [54]. Overall, the data reflects the varying degrees of susceptibility of soybean plants to different post-emergence herbicides reflecting the varying sensitivity of soybean plants to different herbicide modes of action. Treatments with herbicides targeting specific enzymes or metabolic pathways may have induced visible symptoms such as chlorosis or necrosis, contributing to higher susceptibility index scores. Similar results were reported by Singh et al. [55].

S-Metolachlor + Pendimethalin and Pendimethalin alone showed highest effectiveness in reducing weed counts and biomass, which suggests these herbicides could balance weed suppression without significant soybean injury. Our results are similar with Askew et al. [56] and Hager et al. [57] who determined that proficient reduction in dry biomass of weeds was noted when S-Metolachlor and Pendimethalin was applied as in soybean. The Manual Control maintained a weed-free environment throughout the growing season, the Weedy Check (with no weed control) experienced the highest weed counts and corresponding fresh and dry weights, underscoring the detrimental impact of unmanaged weed competition on crop growth [58]. Conversely, treatments like S-Metolachlor + Atrazine + Mesotrione demonstrated high initial weed counts and significant weed biomass at harvest, pointing to their insufficient weed control efficacy over time or potential crop injury leading to reduced competition against weeds. The persistence of weeds in these treatments is further evidenced by the Weed Control Percentage (WCP) and Weed Persistence Index (WPI) where they scored lower compared to the Manual Control, indicating a less effective weed management strategy. While the pre-emergence (PRE) treatments generally provided good control early season, the post-emergence (POST) treatments Mesotrione + Atrazine were necessary to sustain weed control later in the growth cycle [59]. This is crucial as prolonged weed pressure can severely impact crop yield. The Weed Control Efficiency (WCE) and Herbicide Efficiency Index (HEI) highlight that the Manual Control and S-Metolachlor + Pendimethalin maintained high efficiency, suggesting they were successful in controlling weeds without adversely affecting the soybean crop [60]. However, herbicides such as S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium and Mesotrione + Atrazine had no WCE or HEI data, which indicates total crop failure due to herbicide damage. Safdar et al. [61] also reported the highest WCE with S-

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Metolachlor + Pendimethalin herbicide. When comparing these herbicide treatments, several options, including S-Metolachlor + Pendimethalin, Pendimethalin, S-Metolachlor, Fluizefop-p-butyl, consistently displayed high WCE values in both years, indicating effective weed control [59]. These findings emphasize the importance of selecting appropriate herbicides and evaluating their performance over time for successful weed management. These results are in lined with Singh et al. [62]. The results suggest that a tailored approach to herbicide application, considering the timing (PRE vs. POST) and the specific herbicide combinations, is essential for effective weed control in soybean cultivation [61]. Care must be taken to select herbicide treatments that minimize crop injury while maximizing weed suppression to ensure optimal soybean growth and yield. These results were also observed by Kumar et al. [63]. The WMI and AMI strongly imply that these treatments had adverse effects on weed management and agronomic management practices, suggesting a need for reevaluation in weed management strategies to ensure that they do not compromise overall farm efficiency and productivity. These findings emphasize the importance of considering both weed control and agronomic management when choosing herbicide treatments in agriculture [62]. A higher WI indicates more weed presence, which is generally undesirable as it signifies a reduction in crop yield potential due to weed competition. The Manual Control treatment demonstrated a WI of virtually zero, signifying that the weed management practices employed were highly effective, leaving no significant weed competition for the soybean crop. This result aligns with the Manual Control's performance across other metrics, where it consistently provided a weed-free environment conducive to soybean growth. In stark contrast, treatments such as S-Metolachlor + Atrazine + Mesotrione and Topramezone reached a WI of 100, the highest possible score, which suggests these treatments were either ineffective and caused complete soybean plant injury leading to an unobstructed proliferation of weeds [59]. Other treatments, such as S-Metolachlor + Pendimethalin, Pendimethalin, and Fluizefop-p-butyl, indicated more moderate WIs, suggesting these herbicides controlled weeds to a degree without fully eradicating them or harming the soybean plants [62]. This partial weed presence might not be entirely negative, as a certain level of weed competition can stimulate soybean plants to optimize resource use without significantly reducing yield. The WI data complements the previously discussed parameters by providing a cumulative assessment of weed pressure throughout the season. A successful weed management program in soybean cultivation, as evidenced by the data, is one that employs herbicides which control weeds effectively across the growing season without causing damage to the crop, as seen with the Manual Control and certain herbicide combinations that kept WI low while preserving soybean health and productivity. These results are in lined with Kumar et al. [63].

Shorter time to flowering in treatments like S-Metolachlor + Atrazine suggests a possible stimulatory effect, while longer times in treatments like Halosulfuron-methyl hint at herbicide-induced developmental delays. These findings are crucial for understanding the physiological impact of herbicides on soybean's reproductive phase [64]. In contrast, the combination of Pendimethalin + Acetochlor, S-Metolachlor + Atrazine, and Acetochlor + Atrazine displayed increased days to flowering, which might be indicative of a stress response, potentially due to herbicide phytotoxicity or altered micro-environmental conditions affecting the soybean's developmental timeline [65]. Notably, the extreme response to S-Metolachlor + Atrazine + Mesotrione suggests these combinations were phytotoxic enough and kill the plants, thus eliminating any possibility of recording further growth parameters. The plant height data showed greatest stunting observed Atrazine, possibly due to its inhibitory effects on photosynthesis which are critical during the early growth stages [66]. The whole plant weight and seeds per pod further substantiate the detrimental impact of these combinations, as the herbicides that allowed for normal flowering times also supported better biomass accumulation and reproductive success. Ultimately, the data highlights the delicate balance required in herbicide management to control weeds effectively without compromising crop health and yield, with S-Metolachlor + Pendimethalin was viable option for maintaining soybean growth while managing weed pressure, our findings align with those reported by Kim et al. [67], who identified pendimethalin as the most effective pre-emergence herbicide for weed control and enhancing soybean seed yield. While the impact of various pre-emergence and post-emergence herbicides on soybean productivity, as indicated by pods per plant, seeds per plant, 100 grain weight, and seed yield per plant. The treatments with S-Metolachlor + Pendimethalin and Fluizefop-p-butyl in both years, as well as Haloxyfop-p-ethyl in 2023, were notable for maintaining relatively high values across all parameters, suggesting these herbicides were effective in controlling weeds without significantly harming the soybean plants Kundu et al. [68]. Conversely, combinations involving Acetochlor (Pendimethalin + Acetochlor and Acetochlor + Atrazine) consistently led to reduced plant productivity parameters, indicating a possible phytotoxic effect on soybean. In their research, Kulal et al. [64] and Prachand et al. [50] evaluated a range of herbicides for soybean weed management, concluding that pendimethalin for pre-emergence and imazethapyr and quizalofop-p-ethyl for post-emergence were most effective in improving weed control and soybean seed yield. Notably, the S-Metolachlor + Pendimethalin treatment emerged as a promising option, closely mirroring the results of Manual Control, indicating its efficacy in weed suppression without significantly detrimental effects on soybean growth and productivity. This suggests a deleterious impact likely due to Atrazine's mode of action, which can impede photosynthesis. Kulal et al. [69] and Prachand et al. [50] discovered same outcomes, S-Metolachlor + Pendimethalin were particularly effective in achieving superior weed control and promoting higher seed weight in soybean crops. Safdar et al. [61] also reported the similar results that S-Metolachlor + Pendimethalin significantly affect the soybean plant height, whole plant weight, pods plant^{-1}, seeds plant^{-1}, 100 grain weight, and seed yield plant^{-1}. Whereas Pendimethalin + Acetochlor and S-Metolachlor + Atrazine exhibited the most substantial reduction in plant height. Interestingly, some pre-emergence herbicide treatments, such as Pendimethalin and S-Metolachlor, demonstrated a slight recovery in plant height in 2023 compared to 2022. Similar results of application of pendimethalin in soybean were also reported by Malik et al. [70]. Notably, herbicides such as S-Metolachlor + Atrazine + Mesotrione, Topramezone, Mesosulfuron-methyl + Iodosulfuron-methyl sodium and Mesotrione + Atrazine led to complete plant mortality, resulting in no data for growth and yield. These findings highlight the critical role of herbicide selection in shaping soybean yield and underscore the need for informed herbicide management practices in soybean cultivation.

5. Conclusions

Soybean grain yield can be reduced up to 74.5% due to weed infestation. Susceptibility index showed that herbicides have the detrimental effects on soybean growth as compared to the manual control. Some herbicides injured the plant and led to the mortality. In Pre emergence herbicides S-Metolachlor + Pendimethalin have least effect on soybean plant and produce higher seed yield. While in post emergence herbicides Fluizefop-p-butyl perform the best for obtaining maximum grain yield with best weed control.

Supplementary Materials: supplement material will be provided on your demand.

Author Contributions: Muhammad Awais Arshad: Validation; Conducted layout, recording data, visualization; writing – review and editing; writing–original draft; software; formal analysis; investigation; methodology. Rana Nadeem Abbas: Conceived research idea, Supervision of project administration; funding acquisition; writing–review and editing; conceptualization. Abdul Khaliq: Statistical analysis, results elaboration and description, Zaheer Ahmed: Seed provision, Language editing, critical review of manuscript.

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