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Ecological approaches to sustainable soybean production with sequential herbicide applications and their impact on weed dynamics and crop yield

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ABSTRACT

Soybean is an important legume crop which is adversely affected by prolonged weed infestation. With the objective to combat this issue over two consecutive years (2022 and 2023), field experiments were conducted at the Agronomic Research Farm, Department of Agronomy, University of Agriculture Faisalabad. The study contains 11 treatments, sole and sequential application of pre-emergence and post-emergence herbicides including s-metolachlor + pendimethalin; s-metolachlor; fluazifop-p-butyl; haloxyfop-p-ethyl; s-metolachlor + pendimethalin and fluazifop-p-butyl; s-metolachlor + pendimethalin and haloxyfop-p-ethyl; s-metolachlor and fluazifop-p-butyl; s-metolachlor and haloxyfop-p-ethyl; weed-free; weedy check and two hand hoeing (at 30 and 45 days after sowing) replicated three times in a randomized complete block design. Growth parameters, weed-related factors and crop yield were meticulously assessed using standard procedures. The study showed that sequential application of herbicide s-metolachlor + pendimethalin as PRE and fluazifop-p-butyl as POST resulted in increased crop vigor scores (7.70 and 7.83), cumulative leaf area duration (197.86 and 195.86 days), net assimilation rate (2.79 and 2.75 $g \cdot m^{-2} \cdot day^{-1}$), leaf area index (4.75 and 4.78 $m^2 \cdot m^{-2}$), total dry matter (531.49 2022 and 544.65 $g \cdot m^{-2}$), reduced weed cover scores (2.40 and 2.10), lower weed counts (35.67 and 28.67), higher plant population (32.00 and 32.33 m^{-2}), taller plant height (45.00 and 47.00 cm), higher number of pods $plant^{-1}$ (42.60 and 43.37), improved seed yield (1784.84 and 1784.84 $kg \cdot ha^{-1}$), harvest index (36.12% and 37.04%), higher protein content (35.78% and 36.97%), oil content (20.33% and 20.90%), oil yield (386.96 and 402.08 $kg \cdot ha^{-1}$) and effective weed control percentage (44.59% to 75.65% at 45 days after spray), with weed control efficiency (88.62% and 89.16%), weed index showed that it reduced minimum (11.43% and 7.19%) soybean yield, herbicide efficiency index (8.83% and 11.38%) in 2022 and 2023 respectively. So, it is recommended that sequential application of s-metolachlor + pendimethalin as a pre-emergence followed by fluazifop-p-butyl as a post-emergence herbicide optimize soybean growth parameters, yield attributes and quality parameters.

Keywords: ecological weed control, ecological engineering in agriculture, herbicide application strategies, environmental impact of herbicides, integrated crop management, sustainable soybean production.

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 also contains numerous vitamins and carbohydrates (Anwar 2016; Ren et al., 2021; Raza et al., 2021; Zhao et al., 2021). Pakistan spends a huge amount of foreign exchange on soybean, oil seeds and edible oil imports. In Pakistan it is expected to increase in the demand of soybean due to its increasing use in food, poultry industry, livestock industry and marine industry. Therefore, it is needed that local cultivation of soybean must be increased. At present soybean cultivation is facing many challenges such as lack of high yielding well adapted genotypes, proper production technology, biotic and abiotic stresses, climate change and most importantly weed infestation. In the last twenty years' emphasis on soybean breeding was given and huge progress has been made to improve soybean genotypes. However, weed control is still a major limiting factor which can cause up to 60% yield losses. Therefore, it is needed that a comprehensive strategy should be developed to control soybean weeds (Asad et al., 2020). Weed losses have been one of the main factors limiting the yield of soybeans. Early-season competition is the most critical when weeds and crop compete for light, moisture, and nutrients. The decline in soybean grain yield caused by weed infestation which may range from 31% to 84% (Kachroo et al., 2003).

Time of Application is the most important factor which influence the effectiveness of herbicides because the application of herbicide when the weeds are more sensitive to herbicides can control more effectively (Motley et al., 2001). Weeds keep the plant's growth under severe stress, especially in the first 30 days after sowing (DAS) and they can cause up to 68% yield reduction (Gaikwad and Pawar, 2002). Herbicide application timing are effective for removing weeds and increasing yield in this time. (Gaikwad and Pawar, 2002; Vyas and Jain, 2005). The majority of the herbicides recommended for soybean are pre-emergence soil-applied types. Post-emergence herbicides also reduce weeds applied at the time of 20 to 25 days after sowing but weeds continue to sprout throughout the growing season (Grundy et al., 2011). Because of the biology of some weeds that grow in soybean it might be challenging to effectively control weeds with a single herbicide treatment (pre- or post-emergence). Therefore, it is necessary to use herbicides in sequence order to suppress weeds for a longer time of crop growth (Malik et al., 2006 and Vijayalaxmi et al., 2012). Malik et al. (2006) studies has been clearly demonstrated that sequential herbicide application such as pre-emergence and post-emergence was resulted in more effective weed control than any sole application (Deore et al., 2008).

Akter et al. (2016) comparing chemical weed control to hand weeding it was found that soybean yield was statistically comparable. There is a long list of herbicides that are advised for soybean weed management. Some of those are sold in Pakistani marketplaces. A pre-emergence herbicide that inhibits cell division is pendimethalin (Mallory et al., 2003). It leads to the failure of cell division which is caused by the inhibition of tubulin synthesis and the stop of microtubule structure (Chu et al., 2018). The s-metolachlor is a cell division inhibitor (Hudetz et al., 1999). The half-life of metolachlor, an achloroacetamide, is 23 days (O'Connell et al., 1998). Kumar and Jha (2015) carried out an experiment in Southern Agriculture Research Center near Huntley, MT to study effectiveness of different pre and post emergence herbicides. The results showed that s-metolachlor, acetochlor, atrazine, atrazine, mesotrione and sulfentrazone applied as pre-emergence which control the 91% weeds at twelve weeks after treatment. Prachand et al. (2015) conducted an experiment to study the effect of pre and post emergence herbicide with different combination of herbicides to control the weeds in soybean crop. The results showed that the maximum grain yield was recorded in the treatment where herbicides was applied as post emergence. It's found that the maximum nutrients were uptake by soybean crop and lowest by the weed plants. Behera et al. (2015) reported that the pendimethalin pre-emergence application provided efficient control of all species from the earliest stages. Furthermore, when soybeans were in their early stage or second flush, the weeds were difficult to suppress with pendimethalin or chlorimuron-ethyl applications alone. So, the sequential application was more effective. Song et al. (2020) conducted an experiment to control weeds in soybean which based on the sequential application of pre and pot emergence herbicide in Russia. The results revealed that the pre-emergence application of acetochlor showed good weed control which was more than 90%. On the other hand, the post application of bentazon + acifluorfen at 30 days after sowing showed good weed control. According to previous research, applying pre- and post-emergence herbicides in sequence increased soybean yield compared to applying herbicides alone (Johnson, 1971; Soltani et al., 2009). Safdar et al. (2020) laid out an experiment and applied pre-emergences pendimethalin and pendimethalin + S-metolachlor and post emergence herbicides oxyfluorfen, metribuzin, quizalofop-p-ethyl, acetochlor, halosulfuron and topramezone. The results reveled that sequential application herbicides showed significant reduction in weed density up to 94% and up to 88% dry weight. Rupareliya et al. (2020) carried out an experiment the outcomes showed that pendimethalin as pre-emergence fb pre-mix propaquizafop + imazethapyr at 30 DAS, pendimethalin as pre-emergence fb pre-mix sodium acifluorfen + clodinafop-propargyl at 30 DAS improved growth parameters. Pendimethalin is readily absorbed by roots but poorly by shoots, and there is very little translocation from root to shoot and vice versa. After emerging from the soil, treated and afflicted plants die shortly after germination (Costa et al., 2013; Merga and Alemu, 2019). Mahoney et al., (2019) reported that the application of two to three times herbicides the annual grasses can be controlled 100% whereas single application can control 71% to 92% weeds. The results indicated that herbicide application timing can increase 21% to 46% soybean yield compared to untreated soybean. The application timing of synthetic auxin herbicide may significantly affect that how severely soybean height and yield are reduced (Solomon and Bradley, 2014). Al-Khatib and Peterson (1999) discovered that soybean plants treated with dicamba at the time of third trifoliate stage (V3) displayed 66% visual estimates of injury at 7 DAT and 92% injury at 14 DAT. This caused a height decrease of 75% and a grain yield drop of 80%. Andersen et al. (2004) applied at the time of V3 caused 30% to 40% soybean damage at 7 DAT and yield losses of 14% to 34%.

This research on optimizing herbicide application timing in soybean cultivation aligns closely with several Sustainable Development Goals (SDGs), particularly SDG 2: Zero Hunger include enhancing agricultural productivity, ensuring sustainable food production systems, and improving food security and SDG 12: Responsible Consumption and Production. By focusing on weed management with application of s-metolachlor + pendimethalin as PRE and fluazifop-p-butyl as POST significantly contributes to increasing soybean growth yield and quality, thus supporting the goal of doubling agricultural productivity for small-scale food producers (Target 2.3). Demonstrating that herbicide application reduce the competition for weeds and significantly boost plant growth and seed yield so, this research can enhance the incomes and food security of farmers, particularly those in vulnerable and small-scale settings. Furthermore, by identifying effective herbicide application timing controlled the weeds effectively that maintain soil quality by reducing competition for soil nutrients, which promotes sustainable agricultural practices, contributing to resilient agricultural systems capable of withstanding extreme weather conditions and maintaining productivity (Target 2.4). Additionally, the study showed the importance of investing in agricultural research and extension services. Providing empirical data on the benefits of specific weed management practices contributes valuable knowledge that can guide future investments in rural infrastructure and agricultural technologies, aligning with the SDG target of increasing investments to enhance agricultural productive capacity (Target 2.a). So, by addressing critical aspects of agricultural productivity and sustainability, this research on soybean contributes to the broader objectives of SDG 2 which helps to end hunger, achieve food security, and promote sustainable agriculture (United Nations, 2015).

In consideration of the abovementioned challenges and the critical impact of weed interference on soybean production, a significant knowledge gap is evident in determining the optimal timing for herbicide application in the context of Pakistan's weed management. Given the deep influence of weed infestation on reducing soybean yields, it is essential to establish the most effective timing for herbicide application to ensure efficient weed control. Addressing this need, the current study comprehensively examines the patterns and dynamics of weed emergence, thereby facilitating a detailed understanding of the implications of both pre-emergence and post-emergence herbicide applications on crop yield losses. The findings from this research are crucial for developing comprehensive weed control strategies, which are key to enhancing the efficiency and productivity of soybean cultivation.

MATERIALS AND METHODS

The experiment was carried out over the year 2022 and 2023 at the Agronomic Research Farm, Department of Agronomy, University of Agriculture Faisalabad. The experimental site has Latitude: 31.4504° N, Longitude: 73.1350 E, Altitude: 186.4 m. Climatic conditions in these years included a total rainfall of 380 mm in 2022 and 345 mm in 2023, with minimum temperatures of 11.20 °C and 13.00 °C and maximum temperatures of 25.00 °C and 27.00 °C, respectively. The experimental soil was characterized as sandy clay-loam with a pH of 7.7 in 2022 and 7.5 in 2023, nitrogen content of 0.13% and 0.16%, and organic matter content of 0.89% and 0.95% in 2022 and 2023, respectively. A total of 11 treatments were employed and arranged in a randomized complete block design, with each treatment replicated three times to ensure robust statistical analysis. The treatments consisted of T1: s-metolachlor + pendimethalin; T2: s-metolachlor; T3: fluazifop-p-butyl; T4: haloxyfop-p-ethyl; T5: s-metolachlor + pendimethalin & fluazifop-p-butyl;

T6: s-metolachlor + pendimethalin & haloxyfop-p-ethyl; T7: s-metolachlor & fluazifop-p-butyl; T8: s-metolachlor & haloxyfop-p-ethyl; T9: weed-free; T10: weedy check; and T11: two hand hoeing (at 30 and 45 days after sowing). Weed management within the respective periods was carried out meticulously, with regular hand weeding at weekly intervals as applicable. Notably, in treatments labeled as weed-free this signified that weeds were removed at weekly intervals during the specified periods.

Data collection encompassed multiple parameters including the assessment of total dry matter (TDM), leaf area index (LAI), leaf area duration (LAD), crop growth rate (CGR), and net assimilation rate (NAR) to evaluate soybean growth. Furthermore, data on weed density, weed dry weight, and soybean yield attributes were collected. To assess quality, parameters such as protein content and oil content in soybean were determined. To record the growth parameters, first divided the experimental units into two parts one for growth data and 2nd for yield data. Growth data was recorded by destructively harvesting of one-foot square from each experimental unit and converted into one-meter square. First growth data was recorded after thirty days from sowing then other samples were harvested after the interval of 15 days. With the help of electric weigh balance, the fresh weight of all samples was measured immediately after the harvesting. Afterwards, in a sample each fraction was separated such as leaves and stem and weighted again to note the fresh green weight of individual fraction. The 10 g sub sample of each fraction was separated with the help of leaf area meter (LI-3100C) and leaf area was recorded. After this, the sample contain both fractions leave and stem were sun dried for two days to reduce the moisture content. Then placed in an oven at 65±2 for three days to obtain the constant weight. By the help of these leaf area, fresh weight and dry weight measurements further growth parameters were computed.

Crop vigor score: Crop vigor was visually rated at 105 DAS on a scale ranging from 0 to 10. A rating of 0 represented plots with dead or least vigorous crops, while a rating of 10 indicated plots with the most vigorous crop, in line with the scale used by Nikoa et al. (2015). CGR was determined using the formula which evaluates the rate of dry matter accumulation over time:

$$CGR = \frac{W_2 - W_1}{t2 - t1} \tag{1}$$

where: $W1$ and $W2$ represent the values of dry weight at different time points, specifically at times T1 (1st data at 30 DAS) and T2 (at interval of 15 DAS). LAI, an essential indicator of plant growth, was calculated by following the formula

$$LAI = \frac{leaf\ area}{land\ area} \tag{2}$$

Leaf area duration was calculated. LAI_1 and LAI_2 were the leaf area indices of samples taken at time presented by time $t1$ and $t2$ respectively.

$$LAD = \frac{(LAI1 + LAI2)(t2 - t1)}{2} \tag{3}$$

To determine the leaf area per plant, ten randomly selected tagged plants from each treatment. The length (L) and width (W) of the terminal leaflet were measured, and their product was adjusted using a leaf shape correction factor. This information allowed for the calculation of LAI, which is a valuable parameter for quantifying the leaf area and assessing soybean growth. The NAR showed the matter accumulation in per unit canopy area of plant. The net progress of dry matter was shown after respiratory losses in plants. The net assimilation rate (*NAR*) has been calculated.

$$NAR = \frac{TDM}{LAD} \tag{4}$$

Weed cover score is a visual observation was conducted before weed removal and evaluated on a scale of 1 to 10, where 1 represented a completely weed-free situation, and 10 represented complete weed coverage, following the scale described by Adigun et al. (2017). Weed density was determined by counting the number of weed species within a 1 m^{-2} quadrat placed randomly at three locations within each plot at 25, 40, 55 DAS, and at harvest. Weeds were harvested by cutting them at ground level, oven-dried at 70 °C for 72 hours, and their dry weight recorded in grams per square meter (g m^{-2}). Weed indices was also recorded including weed control efficiency and other following standard procedures as follows: The weed control efficiency (WCE) is expressed as a percentage.

$$WCE = \frac{W_C - W_T}{W_C} \times 100 \tag{5}$$

where: W_C – weed dry weight in control (unweeded) plot. W_T – weed dry weight in treated plot.

To calculate the *WI*, we use two values: the yield from a plot without weeds (Y_{WF}) and the yield from the treated plot (Y_T). We use a simple formula to find the *WI*:

$$WI = \frac{Y_{WF} - Y_T}{Y_{WF}} \times 100 \quad (6)$$

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:

$$WPI = \frac{W_T}{W_C} \times \frac{W_{PC}}{W_{pT}} \quad (7)$$

The *WMI* 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):

$$WMI = \frac{\frac{Y_T - Y_C}{Y_C}}{\frac{W_C - W_T}{W_C}} \quad (8)$$

The agronomic management index (*AMI*) 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):

$$AMI = \frac{\frac{Y_T - Y_C}{Y_c} - \frac{W_C - W_T}{W_C}}{\frac{W_C - W_T}{W_C}} \quad (9)$$

Statistical analysis

The data pertaining to all response variables under investigation were recorded, thoroughly arranged and subjected to statistical analyses Statistix 8.1 software. Consequently, data were averaged for clarity in treatment comparisons. Statistical significance among treatments was assessed through fisher's analysis of variance (ANOVA), followed by the least significant difference (LSD) test at a 5% probability level ($P \leq 0.05$) for detailed treatment mean comparisons. 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. The graphical presentation was done by Origin 2024b.

RESULTS

The research has yielded significant findings regarding the level of infestation by various weed species during the crop growth period over two consecutive years, 2022 and 2023. The results in Table 1 showed the infestation rates of broadleaf weeds grasses, and sedges, classified under their respective plant families. In the category of broadleaf weeds, *Tribulus terrestris* L. from the Aizoaceae family showed a consistently

Table 1. Weed species and their level of infestation during the period of crop growth in 2022 and 2023

Weed species	Plant family	Level of infestation	
		2022	2023
Broad leaf weeds			
Tribulus terrestris L.	Aizoaceae	***	***
Convolvulus arvensis (Linn)	Convolvulaceae	**	***
Trianthema portulacastrum (Linn)	Zygophyllaceae	*	**
Xanthium strumarium L.	Compositae	–	*
Euphorbia hirta L.	Euphorbiaceae	*	–
Euphorbia granulate L.	Euphorbiaceae	*	*
Parthenium hysterophorus L.	Asteraceae	-	*
Grasses			
Cynodon dactylon (L) Gaertn	Poaceae	**	***
Paspalum distichum (L)	Poaceae	*	*
Phalaris minor Retz.	Poaceae	-	*
Sedge			
Cyperus difformis	Cyperaceae	**	***
Cyperus esculentus	Cyperaceae	*	*
Cyperus rotundus	Cyperaceae	*	–

high level of infestation (60–90%) in both years. The infestation levels of *Convolvulus arvensis* L. from the Convolvulaceae family increased from moderate (30–59%) in 2022 to high in 2023. *Trianthema portulacastrum* L. from the Zygophyllaceae family showed an increase in infestation from low (1–29%) in 2022 to moderate in 2023. Other species such as *Xanthium strumarium* L., *Euphorbia hirta* L., *Euphorbia granulata* L., and *Parthenium hysterophorus* L. varied from non-noticeable to low infestation levels over the two years. Among the grasses, *Cynodon dactylon* (L) Gaertn from the Poaceae family showed an increase in infestation from moderate to high. *Paspalum distichum* (L) maintained a low infestation level across both years, and *Phalaris minor* Retz. Recorded with low level infestation in 2023. In sedges the *Cyperus difformis* was moderate infestation in 2022 which increase to high in 2023. *Cyperus esculentus* remained at a low infestation level across the two years. Conversely, *Cyperus rotundus*, which had a low infestation level in 2022, was not noticeable in 2023.

The results of the crop vigor scores showed clear differences between treatments during both years. The higher vigor score 7.70 and 7.83 was recorded when the sequential application of s-metolachlor + pendimethalin as PRE and fluazifop-p-butyl as POST was applied in 2022. While the sole application of post emergence herbicides resulted lowest vigor score 4.64 in fluazifop-p-butyl and 4.12 in haloxyfop-p-ethyl. In comparison, the weed-free condition showed the highest vigor score of 8.74 while the weedy check had the lowest score of 3.47. Manual hoeing treatments demonstrated intermediate vigor scores showing moderate effectiveness compared to herbicide treatments and weed-free conditions. Similar trends were observed in 2023, with sequential herbicide applications recorded highest vigor scores followed by weed-free conditions. The analysis of cumulative leaf area duration (LAD) across both 2022 and 2023 showed significant variations among the treatments. In both years, treatments combining s-metolachlor + pendimethalin and fluazifop-p-butyl applied pre and post-emergence consistently showed the highest LAD, showing prolonged leaf area development throughout the growth stages of soybean. In 2022 these combined herbicide treatments recorded LAD values of 197.86 and 200.14, while in 2023, they reached 195.86 and 189.50, respectively. These were notably higher compared to treatments with sole pre or post-emergence herbicides which showed LAD ranging from 128.10 to 162.46. When compared to these herbicide treatments, two hand hoeing treatments showed comparable efficacy in promoting leaf area development with LAD ranging from 173.27 to 175.84 in both years. In 2022, sequential application of s-metolachlor + pendimethalin and fluazifop-p-butyl applied pre and post-emergence, showed the highest net assimilation rate (NAR) with respectively 2.79 and 2.92. These were notably higher compared to treatments with sole pre or post-emergence herbicides which ranged from 2.61 to 2.68. In 2023, the sequential application herbicide displayed the highest NAR with s-metolachlor + pendimethalin & fluazifop-p-butyl (PRE & POST) reaching 2.75 and 2.81, respectively (Table 2). While the lowest NAR values were observed in sole post-emergence herbicides and the weedy check condition showing inferior assimilation rates. Interestingly, two hand hoeing showed moderate NAR ranging from 2.75 to 2.79 both years, suggesting comparable efficacy to certain herbicide treatments in promoting assimilation rates.

The line graph depicted in Figure 1 portrays the leaf area index (LAI) incorporating sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl consistently showed early leaf area development evident from their higher LAI at early growth stages (0.756 to 2.856 in 2022 and 0.855 to 3.008 in 2023).

At 30 days after sowing (DAS), the combination of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl showed LAI of 0.855 showing robust early leaf area development. Similarly, at 45 and 60 DAS, this treatment combination maintained higher LAI of 2.024 and 3.008, respectively. While post-emergence herbicide treatments, such as fluazifop-p-butyl and haloxyfop-p-ethyl, displayed slower leaf area expansion as showed by their comparatively lower LAI across most intervals (0.404 to 2.232 in 2022 and 0.406 to 2.024 in 2023). Notably, the weed-free condition consistently showed the highest LAI in both years (0.856 to 3.194 in 2022 and 0.914 to 3.175 in 2023). Additionally, two hand hoeing treatments showed LAI comparable to certain herbicide treatments, particularly during later growth stages (0.420 to 4.552 in 2022 and 0.555 to 4.764 in 2023), suggesting their efficacy in enhancing leaf area development. The total dry matter accumulation in soybeans, as depicted in Figure 2 for the years 2022 and 2023, respectively, revealed clear patterns influenced

Table 2. Effect of herbicide application time on crop vigor, cumulative leaf area duration and net assimilation rate of soybean crop

Treatments	Time of application	Dose	Crop vigor score		Cumulative LAD		Net assimilation rate (NAR)	
			2022	2023	2022	2023	2022	2023
S-Metolachlor + Pendimethalin	PRE	900 ml acre^{-1}	5.81±0.08^{f}	6.12±0.06^{e}	162.46±0.14^{f}	166.07±0.75^{f}	2.68±0.01^{ef}	2.78±0.01^{cd}
S-Metolachlor	PRE	800 ml acre^{-1}	5.37±0.12^{g}	5.75±0.07^{f}	157.57±0.42^{g}	156.54±0.32^{g}	2.66±0.01^{f}	2.75±0.01^{e}
Fluazifop-p-butyl	POST	800 ml acre^{-1}	4.64±0.10^{h}	5.29±0.09^{g}	143.09±0.04^{h}	146.12±1.05^{h}	2.64±0.02^{fg}	2.71±0.02^{f}
Haloxyfop-p-ethyl	POST	350 ml acre^{-1}	4.12±0.06^{i}	4.42±0.08^{h}	128.10±0.64^{i}	128.88±0.49^{i}	2.61±0.02^{g}	2.67±0.01^{g}
S-Metolachlor + Pendimethalin & Fluazifop-p-butyl	PRE & POST	900 & 800 ml acre^{-1}	7.70±0.09^{b}	7.83±0.10^{b}	197.86±0.48^{b}	200.14±0.36^{b}	2.79±0.01^{b}	2.92±0.02^{b}
S-Metolachlor + Pendimethalin & Haloxyfop-p-ethyl	PRE & POST	900 & 350 ml acre^{-1}	7.32±0.12^{c}	7.56±0.10^{bc}	189.50±0.57^{c}	195.86±0.40^{c}	2.75±0.01^{bc}	2.81±0.01^{c}
S-Metolachlor & Fluazifop-p-butyl	PRE & POST	800 & 800 ml acre^{-1}	6.72±0.08^{d}	7.31±0.08^{c}	175.89±0.32^{d}	185.52±0.92^{d}	2.72±0.01^{cd}	2.75±0.02^{de}
S-Metolachlor & Haloxyfop-p-ethyl	PRE & POST	800 & 350 ml acre^{-1}	6.43±0.07^{e}	6.34±0.11^{e}	171.03±1.22^{e}	174.12±0.03^{e}	2.70±0.02^{de}	2.73±0.02^{ef}
Weed free	–	–	8.74±0.10^{a}	8.19±0.10^{a}	218.45±0.50^{a}	222.85±1.14^{a}	3.20±0.01^{a}	3.11±0.01^{a}
Weedy Check	–	–	3.47±0.10^{j}	2.89±0.13^{i}	105.98±0.25^{j}	112.64±0.24^{j}	2.57±0.01^{h}	2.57±0.01^{h}
Two hand hoeing	30 & 45 DAS	–	6.21±0.05^{e}	6.72±0.08^{d}	173.27±2.13^{e}	175.84±0.59^{e}	2.75±0.03^{c}	2.79±0.01^{c}
MS for treatment			7.52447**	7.54320**	3042.39**	3122.39**	0.08332**	0.05753**
LSD at 5%			0.2558	0.2745	2.4825	2.0390	0.0382	0.0331

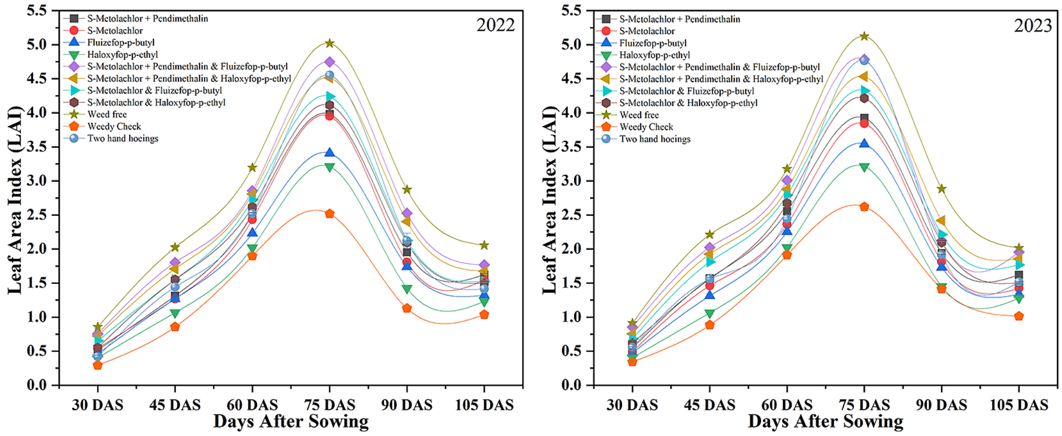


Figure 1. Comparative analysis of leaf area index (LAI) under various weed management practices in 2022 and 2023

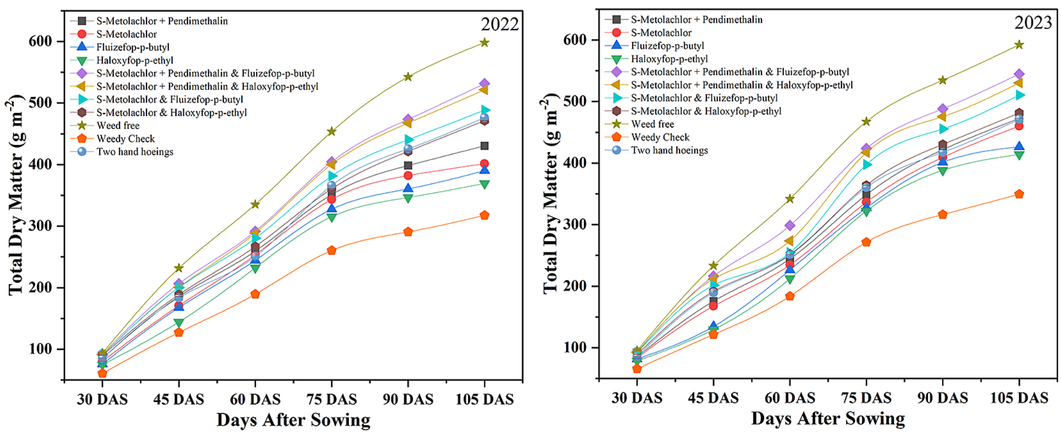


Figure 2. Comparative analysis of total dry matter (TDM) under various weed management practices in 2022 and 2023

by various herbicide applications and timing. The combination of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl showed the highest dry matter accumulation throughout the growth stages (92.458 g to 531.490 g in 2022; 93.598 g to 544.651 g in 2023), indicating their effectiveness in promoting soybean biomass production. while post-emergence herbicide such as fluazifop-p-butyl and haloxyfop-p-ethyl showed relatively lower total dry matter values across most intervals (75.871 g to 369.483 g in 2022; 78.538 g to 414.276 g in 2023), suggesting a less pronounced impact on biomass accumulation. Particularly, the weed-free condition consistently showed the highest total dry matter (93.445 g to 598.240 g in 2022; 95.591 g to 592.218 g in 2023) showing the detrimental effects of weed competition on soybean biomass development. Two hand hoeing treatments showed total dry matter comparable to certain herbicide, especially during later growth stages (85.245 g to 476.201 g in 2022; 86.371 g to 471.284 g in 2023) showing their potential in enhancing soybean biomass production. The analysis of crop growth rate (CGR) data from 2022 and 2023 showed various trends influenced by herbicide application timing and types (Fig. 3). In both years, pre-emergence herbicide treatments particularly those with s-metolachlor + pendimethalin or s-metolachlor alone showed higher CGR compared to post-emergence treatments. The sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl displayed the highest CGR ranging from approximately 3.016 to 9.581 across various intervals. While, post-emergence herbicides like fluazifop-p-butyl and haloxyfop-p-ethyl showed lower CGR ranging from approximately 1.672 to 7.492. Notably, the weed-free condition consistently had the highest CGR ranging from approximately 4.594 to 8.373, while two hand hoeing treatments showed CGR values ranging from approximately 3.441 to 7.319.

The assessment of weed cover scores in soybeans for both 2022 and 2023 presented in Table 3, explains distinct trends influenced by herbicide application timing and types. The Sequential application pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl showed the lowest weed cover scores, indicating superior weed control efficacy.

S-metolachlor + pendimethalin & fluazifop-p-butyl (PRE & POST) showed weed cover scores of 2.40 in 2022 and 2.10 in 2023 suggesting effective weed suppression. Pre-emergence herbicide applications particularly s-metolachlor + pendimethalin and s-metolachlor alone generally showed lower weed cover scores compared to post-emergence treatments. In 2022, s-metolachlor + pendimethalin (PRE) recorded a weed cover score of 5.70 while in 2023, it decreased to 4.80. Similarly, s-metolachlor (PRE) showed weed cover scores of 6.53 in 2022 and 5.10 in 2023. While, post-emergence herbicides fluazifop-p-butyl and haloxyfop-p-ethyl displayed relatively higher weed cover scores indicating less effective weed suppression. In 2022, fluazifop-p-butyl (POST) and haloxyfop-p-ethyl (POST) exhibited weed cover scores of 7.10 and 7.50, respectively, while in 2023, these scores decreased to 5.50 and 6.60. Additionally, two hand hoeing treatments displayed competitive weed cover scores, ranging from 5.27 to 4.30 in 2022 and 4.30 to 4.30 in 2023. Similarly, pre-emergence herbicide treatments such as

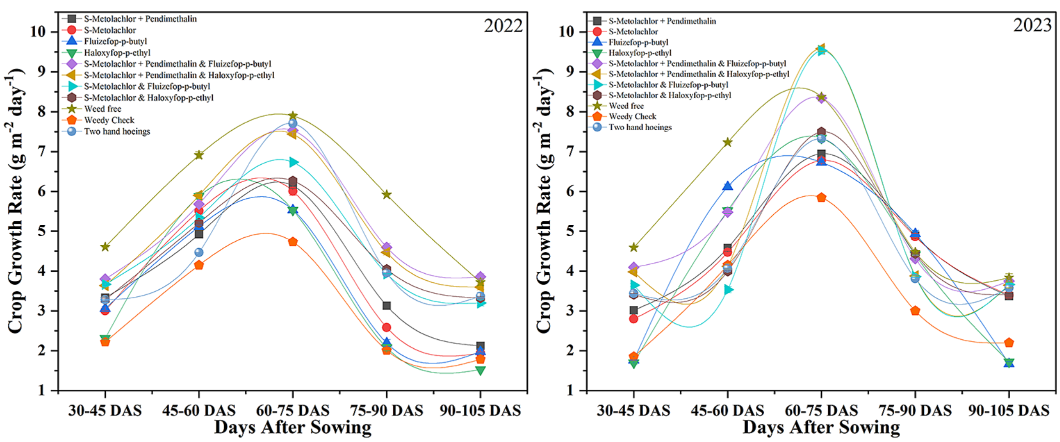


Figure 3. Comparative analysis of crop growth rate (CGR) under various weed management practices in 2022 and 2023

Table 3. Effect of herbicide application time on weeds density at different interval and weeds dry weight in soybean

Treatments	Time of application	Dose	Weeds cover score		Initial weed count before herbicides		Weed count after 15 days spray		Weed count after 30 days spray		Weed count after 45 days spray		Weeds dry weight at harvest kg ha^{-1}	
			2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
S-Metolachlor + Pendimethalin	PRE	900 ml acre^{-1}	5.70±0.06^{e}	4.80±0.09^{e}	0.00±0.00^{h}	0.00±0.00^{h}	133.00±4.04^{e}	98.00±4.06^{e}	151.67±6.17^{d}	105.33±4.33^{e}	154.33±4.33^{d}	104.33±4.10^{de}	1724.25±20.23^{e}	1304.84±12.43^{e}
S-Metolachlor	PRE	800 ml acre^{-1}	6.53±0.09^{d}	5.10±0.06^{d}	0.00±0.00^{h}	0.00±0.00^{h}	155.33±5.24^{d}	112.00±4.09^{d}	173.67±5.24^{c}	122.00±5.69^{d}	168.00±4.04^{c}	116.33±2.03^{cd}	2038.95±18.46^{d}	1449.27±16.90^{d}
Fluazifop-p-butyl	POST	800 ml acre^{-1}	7.10±0.06^{c}	5.50±0.09^{c}	324.33±6.17^{b}	252.00±4.04^{c}	217.00±4.09^{c}	188.67±3.76^{c}	202.67±3.76^{b}	155.33±5.24^{c}	182.67±5.78^{b}	126.00±5.86^{bc}	2279.67±17.39^{c}	1770.75±19.39^{c}
Haloxyfop-p-ethyl	POST	350 ml acre^{-1}	7.50±0.06^{b}	6.60±0.06^{b}	345.67±7.13^{a}	273.00±4.04^{b}	231.00±4.17^{b}	204.00±4.93^{b}	214.67±6.17^{b}	178.33±5.78^{b}	193.00±4.62^{b}	135.33±6.17^{b}	2401.89±18.39^{b}	1909.48±17.63^{b}
S-Metolachlor + Pendimethalin & Fluazifop-p-butyl	PRE & POST	900 & 800 ml acre^{-1}	2.40±0.09^{j}	2.10±0.06^{j}	147.00±4.04^{g}	119.00±4.04^{g}	81.67±6.17^{h}	63.00±4.04^{g}	56.33±4.33^{g}	48.67±3.76^{h}	35.67±3.48^{h}	28.67±4.63^{h}	432.98±23.29^{j}	386.99±17.43^{j}
S-Metolachlor + Pendimethalin & Haloxyfop-p-ethyl	PRE & POST	900 & 350 ml acre^{-1}	3.30±0.06^{i}	3.03±0.03^{i}	170.33±6.17^{f}	141.00±4.93^{f}	96.33±3.28^{g}	77.00±4.04^{f}	70.67±4.63^{f}	63.67±4.63^{g}	48.67±3.76^{gh}	42.67±4.63^{g}	562.95±14.40^{i}	503.17±12.42^{i}
S-Metolachlor & Fluazifop-p-butyl	PRE & POST	800 & 800 ml acre^{-1}	4.25±0.03^{h}	3.60±0.06^{h}	210.00±4.04^{e}	196.00±4.04^{e}	111.67±3.76^{f}	92.00±4.93^{e}	77.33±3.76^{ef}	75.67±3.76^{fg}	56.67±5.61^{g}	51.00±5.86^{fg}	671.87±12.48^{h}	557.34±20.86^{h}
S-Metolachlor & Haloxyfop-p-ethyl	PRE & POST	800 & 350 ml acre^{-1}	4.70±0.06^{g}	4.10±0.06^{g}	238.00±4.04^{d}	217.00±4.04^{d}	117.00±6.43^{f}	98.00±4.12^{e}	91.00±4.04^{e}	79.33±5.49^{f}	71.67±4.33^{f}	64.00±4.93^{f}	804.91±7.77^{g}	665.45±13.59^{g}
Weed free	-	-	-	-	331.33±6.17^{ab}	282.33±6.17^{b}	0.00±0.00^{i}	0.00±0.00^{h}	0.00±0.00^{h}	0.00±0.00^{i}	0.00±0.00^{i}	0.00±0.00^{i}	0.00±0.00^{k}	0.00±0.00^{k}
Weedy Check	-	-	9.10±0.06^{a}	8.30±0.06^{a}	323.33±5.24^{b}	296.00±5.20^{a}	326.67±6.17^{a}	301.33±4.33^{a}	329.00±4.04^{a}	308.00±4.04^{a}	329.00±5.29^{a}	309.33±5.24^{a}	3804.79±15.53^{a}	3569.86±17.94^{a}
Two hand hoeing	30 & 45 DAS	-	5.27±0.06^{f}	4.30±0.03^{f}	305.67±6.17^{c}	245.00±4.04^{c}	209.67±3.18^{c}	188.33±4.63^{c}	203.00±4.04^{b}	176.00±3.21^{b}	118.33±4.10^{e}	92.00±4.93^{e}	1548.80±15.34^{f}	1212.59±14.95^{f}
MS for treatment			19.6616**	14.7248	48616.6**	34049.3**	23600.5**	20905.3**	26434.6**	20887.8**	26750.7	20455.5**	3752177**	2940729**
LSD at 5%			0.1803	0.1500	14.636	11.841	12.099	9.1065	13.812	12.860	13.370	13.465	47.825	47.841

s-metolachlor + pendimethalin and s-metolachlor alone generally resulted in lower weed counts and dry weights compared to post-emergence applications. Sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl showed the lowest weed counts and dry weights, indicating superior weed control efficacy. S-metolachlor + pendimethalin & fluazifop-p-butyl (PRE & POST) showed an initial weed count of 81.67 in 2022 decreasing to 63.00 in 2023, with corresponding dry weights of 432.98 and 386.99 kg·ha^{-1}. In 2022, s-metolachlor + pendimethalin (PRE) recorded an initial weed count of 133.00, which decreased to 98.00 after 15 days and further to 105.33 after 30 days. Similarly, in 2023, the initial weed count recorded from 0.00 to 4.80 after 45 days under the same treatment. While post-emergence herbicides fluazifop-p-butyl and haloxyfop-p-ethyl showed higher weed counts and dry weights showing less effective weed suppression. Fluazifop-p-butyl (POST) had an initial weed count of 324.33 in 2022 and 252.00 in 2023 with corresponding dry weights of 2279.67 and 1770.75 kg·ha^{-1}, respectively. Additionally, two hand hoeing treatments displayed competitive results although with slightly higher weed counts and dry weights compared to certain herbicide treatments. At 45 DAS the two hand hoeing showed a weed count of 118.33 and a dry weight of 1548.80 kg·ha^{-1} which decreased to 92.00 and 1212.59 kg·ha^{-1}, respectively, in 2022 and 2023 (Table 3).

The results showed notable variations in soybean yield attributes influenced by herbicide application time. The sequential application of s-metolachlor + pendimethalin and fluazifop-p-butyl applied PRE & POST consistently displayed the highest plant population in both years with values of 32.00 m^{-2} in 2022 and 32.33 m^{-2} in 2023. This showed approximately 14% increase in plant population compared to the lowest performing herbicide treatment, fluazifop-p-butyl applied POST, which showed plant populations of 27.00 m^{-2} in 2022 and 27.67 m^{-2} in 2023. Two hand hoeing resulted in plant populations of 31.00 m^{-2} in both 2022 and 2023, showing approximately a 19% increase over the lowest herbicide treatment. In terms of days to flowering, s-metolachlor + pendimethalin applied PRE showed shortest duration during both years with 52.00 days in 2022 and 51.67 days in 2023. This showed approximately a 5% reduction in days to flowering compared to the herbicide treatment with the longest duration, s-metolachlor + haloxyfop-p-ethyl applied PRE & POST, which had flowering durations of 58.00 days in 2022 and 56.33 days in 2023. Two hand hoeing at 30 & 45 DAS resulted in days to flowering of 50.67 days in 2022 and 50.00 days in 2023, showing a 14% decrease compared to the longest duration herbicide treatment. Regarding plant height, s-metolachlor + pendimethalin applied PRE led to the tallest plants in both years, with heights of 45.00 cm in 2022 and 47.00 cm in 2023. It showed the increase of 27% plant height as compared to the haloxyfop-p-ethyl applied as post which is 40.33 cm and 43.67 in 2022 and 2023 respectively. Whereas the hand hoeing showed 44 and 47.33 cm plant height in 2022 and 2023 respectively which is 19% increase then shortest herbicide treatment. Similarly, the sequential application of s-metolachlor + pendimethalin & fluazifop-p-butyl applied PRE & POST produced the higher number of pods·plant^{-1} (42.60 in 2022 and 43.37 in 2023) seed·pod^{-1} (3.23 in 2022 and 3.57 in 2023) seeds· plant^{-1} (120.11 in 2022 and 122.46 in 2023) (Table 4) 100 grain weight (11.49 g in 2022 and 11.72 g in 2023) Stover yield (3246.55 kg·ha^{-1} in 2022 and 3431.66 kg·ha^{-1} in 2023) biological yield (5093.39 kg·ha^{-1} in 2022 and 5418.86 kg·ha^{-1} in 2023) during both years. While, haloxyfop-p-ethyl applied POST showed the lowest number pods·plant^{-1} (35.97 in 2022 and 35.57 in 2023) seed pod^{-1} (2.10 in 2022 and 2.43 in 2023) seeds plant^{-1} (97.54 in 2022 and 98.5 in 2023) 100 grain weight (10.27 g in 2022 and 10.31 g in 2023) Stover yield (2785.92 kg·ha^{-1} in 2022 and 2903.77 kg·ha^{-1} in 2023) biological yield (4304.88 kg·ha^{-1} in 2022 and 4539.12 kg·ha^{-1} in 2023) in both 2022 and 2023 (Table 5).

Whereas two hand hoeing showed 36% increase in number of pods then the lower herbicide treatment. Whereas the hand hoeing showed 3.02 and 3.03 seed per pods and 100-grain weight 11.00 and 11.15 grams at par with pre emergence herbicides in 2022 and 2023 respectively. While the hand hoeing showed 111.52 and 107.53 seeds per plant similar with post-emergence herbicide in 2022 and 2023 respectively. Furthermore, two hand hoeing treatments showed stover yields comparable to pre-emergence herbicide applications averaging 3255.36 kg·ha^{-1} in 2022 and 3345.21 kg·ha^{-1} in 2023. Additionally, they demonstrated biological yields comparable to herbicide applications with an average of 5005.68 kg·ha^{-1} in 2022 and 5202.79 kg·ha^{-1} in 2023. In terms of seed yield (kg·ha^{-1}) of soybeans for both years the Pre-emergence herbicide applications generally resulted in higher seed yields compared to post-emergence applications. Treatments with s-metolachlor + pendimethalin applied pre-emergence showed an average seed yield of 1646.58 kg·ha^{-1} in 2022 and 1784.84 kg·ha^{-1} in 2023, while pre-emergence s-metolachlor treatments showed 1612.57 kg·ha^{-1} in 2022 and 1716.21 kg·ha^{-1} in 2023. Post-emergence herbicide applications fluazifop-p-butyl and haloxyfop-p-ethyl, resulted in lower seed yields, with an average of 1584.46 kg·ha^{-1} in 2022 and 1656.51 kg·ha^{-1} in

Table 4. Effect of herbicide application time on growth and yield attributes of soybean

Treatments	Time of application	Dose	Plant population m^{-2}		Days to flowering (days)		Plant height (cm)		Number of pods plant^{-1}		Number of seeds pod^{-1}		Number of seeds plant^{-1}	
			2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
S-Metolachlor + Pendimethalin	PRE	900 ml acre^{-1}	30.00±0.58^{b}	30.67±0.67^{bc}	52.00±0.88^{de}	51.67±0.33^{de}	45.00±0.58^{b}	47.00±0.88^{b}	38.07±0.38^{ef}	39.53±0.55^{d}	2.90±0.15^{c}	2.87±0.09^{cd}	106.48±0.43^{e}	105.58±0.55^{e}
S-Metolachlor	PRE	800 ml acre^{-1}	27.67±0.88^{c}	28.67±0.33^{de}	53.00±0.58^{d}	52.00±0.88^{d}	43.33±0.33^{c}	46.00±0.58^{bc}	37.07±0.30^{fg}	37.40±0.68^{e}	2.30±0.06^{d}	2.67±0.09^{de}	104.95±0.94^{e}	101.46±0.44^{f}
Fluazifop-p-butyl	POST	800 ml acre^{-1}	27.00±0.58^{c}	27.67±0.88^{ef}	55.00±0.58^{c}	53.00±0.58^{cd}	41.00±0.58^{d}	44.67±0.33^{cd}	36.37±0.55^{g}	35.77±0.43^{ef}	2.20±0.15^{d}	2.50±0.12^{e}	99.43±0.69^{f}	100.77±0.69^{fg}
Haloxyfop-p-ethyl	POST	350 ml acre^{-1}	26.33±0.33^{c}	26.67±0.88^{f}	55.33±0.88^{c}	53.33±0.33^{bcd}	40.33±0.33^{de}	43.67±0.33^{de}	35.97±0.35^{g}	35.57±0.61^{f}	2.10±0.06^{d}	2.43±0.09^{e}	97.54±0.89^{f}	98.65±0.48^{g}
S-Metolachlor + Pendimethalin & Fluazifop-p-butyl	PRE & POST	900 & 800 ml acre^{-1}	32.00±0.58^{ab}	32.33±0.67^{ab}	56.00±0.58^{bc}	54.33±0.33^{bc}	40.00±0.58^{de}	42.00±0.58^{fg}	42.60±0.51^{ab}	43.37±0.28^{a}	3.23±0.09^{b}	3.57±0.09^{ab}	120.11±1.00^{b}	122.46±0.62^{b}
S-Metolachlor + Pendimethalin & Haloxyfop-p-ethyl	PRE & POST	900 & 350 ml acre^{-1}	32.00±0.58^{ab}	32.00±0.58^{ab}	57.00±0.58^{ab}	55.00±0.58^{ab}	39.00±0.58^{ef}	40.33±0.33^{h}	41.50±0.61^{c}	43.17±0.20^{ab}	3.13±0.12^{bc}	3.37±0.03^{b}	118.22±0.83^{b}	118.67±0.77^{c}
S-Metolachlor & Fluazifop-p-butyl	PRE & POST	800 & 800 ml acre^{-1}	31.33±0.88^{ab}	31.67±0.33^{abc}	56.33±0.33^{bc}	54.00±0.58^{bc}	41.33±0.33^{d}	43.00±0.58^{ef}	40.00±0.25^{d}	41.57±0.58^{bc}	3.03±0.12^{bc}	3.10±0.06^{c}	115.63±0.43^{c}	112.47±0.79^{d}
S-Metolachlor & Haloxyfop-p-ethyl	PRE & POST	800 & 350 ml acre^{-1}	31.00±0.58^{ab}	30.00±0.58^{cd}	58.00±0.58^{a}	56.33±0.88^{a}	38.33±0.33^{fg}	41.00±0.58^{gh}	39.47±0.66^{de}	40.60±0.75^{cd}	3.00±0.10^{bc}	3.00±0.06^{c}	112.10±0.70^{d}	114.76±0.58^{d}
Weed free	-	-	32.67±0.88^{a}	32.67±0.33^{a}	49.67±0.33^{f}	48.67±0.33^{f}	48.00±0.58^{a}	50.00±0.58^{a}	43.40±0.62^{a}	43.93±0.82^{a}	3.63±0.09^{a}	3.70±0.06^{a}	126.81±0.69^{a}	130.74±0.60^{a}
Weedy check	-	-	22.33±0.88^{d}	23.33±0.88^{g}	51.67±0.33^{de}	49.00±0.58^{f}	37.00±0.58^{g}	38.33±0.33^{i}	29.63±0.26^{h}	31.87±0.33^{g}	2.03±0.12^{d}	2.07±0.09^{f}	68.31±0.69^{g}	66.22±1.82^{h}
Two hand hoeing	30 & 45 DAS	-	31.00±0.58^{ab}	31.00±0.58^{abc}	50.67±0.33^{ef}	50.00±0.58^{ef}	44.00±0.58^{bc}	47.33±0.33^{b}	40.50±0.47^{cd}	43.37±0.62^{a}	3.00±0.06^{bc}	3.03±0.09^{c}	111.52±0.61^{d}	107.53±0.56^{e}
MS for treatment			30.4545**	24.7636**	23.2545**	18.4909**	31.3394**	36.0545**	44.6190**	48.0982**	0.84618**	0.74497**	737.260**	849.917**
LSD at 5%			2.1236	1.9487	1.6640	1.6719	1.5434	1.4705	1.4052	1.7068	0.3215	0.2385	2.2921	2.4377

Table 5. Effect of herbicide application time on growth and yield attributes of soybean

Treatments	Time of application	Dose	100 grain weight (g)		Seed yield (kg ha $^{-1}$)		Stover yield (kg ha $^{-1}$)		Biological yield (kg ha $^{-1}$)		Harvest index (%)	
			2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
S-Metolachlor + Pendimethalin	PRE	900 ml acre $^{-1}$	10.93±0.06^{e}	11.02±0.03^{ef}	1646.58±5.84^{f}	1784.84±7.57^{g}	2912.39±5.11^{g}	3033.73±5.21^{f}	4558.97±10.93^{f}	4818.57±11.65^{f}	36.12±0.04^{de}	37.04±0.08^{b}
S-Metolachlor	PRE	800 ml acre $^{-1}$	10.88±0.08^{e}	10.84±0.04^{f}	1612.57±5.52^{g}	1716.21±7.18^{h}	2976.86±6.73^{f}	3094.07±6.61^{e}	4589.43±10.38^{f}	4810.28±11.68^{f}	35.14±0.07^{fg}	35.68±0.09^{g}
Fluazifop-p-butyl	POST	800 ml acre $^{-1}$	10.31±0.06^{f}	10.46±0.10^{g}	1584.46±6.64^{h}	1656.51±5.51^{i}	2815.99±6.67^{h}	2955.69±5.79^{g}	4400.45±11.47^{g}	4612.21±11.30^{g}	36.01±0.08^{e}	35.92±0.03^{f}
Haloxyfop-p-ethyl	POST	350 ml acre $^{-1}$	10.27±0.09^{f}	10.31±0.12^{g}	1518.95±7.77^{i}	1635.42±4.98^{j}	2785.92±6.98^{i}	2903.70±5.84^{h}	4304.88±14.75^{h}	4539.12±10.82^{h}	35.28±0.06^{f}	36.03±0.02^{f}
S-Metolachlor + Pendimethalin & Fluazifop-p-butyl	PRE & POST	900 & 800 ml acre $^{-1}$	11.49±0.05^{b}	11.72±0.04^{b}	1846.83±6.41^{b}	1987.21±5.59^{b}	3246.55±4.99^{a}	3431.66±6.35^{a}	5093.39±11.32^{b}	5418.86±11.90^{b}	36.26±0.05^{d}	36.67±0.02^{c}
S-Metolachlor + Pendimethalin & Haloxyfop-p-ethyl	PRE & POST	900 & 350 ml acre $^{-1}$	11.38±0.10^{b}	11.69±0.10^{b}	1804.58±6.39^{c}	1963.83±5.80^{c}	3203.71±7.86^{b}	3398.69±7.19^{b}	5008.29±12.14^{c}	5362.53±12.99^{c}	36.03±0.08^{e}	36.62±0.02^{cd}
S-Metolachlor & Fluazifop-p-butyl	PRE & POST	800 & 800 ml acre $^{-1}$	11.23±0.08^{c}	11.43±0.07^{c}	1784.42±6.07^{d}	1924.26±7.29^{d}	3028.49±6.84^{d}	3386.69±6.67^{b}	4812.91±12.89^{d}	5310.96±11.99^{d}	37.08±0.03^{b}	36.23±0.08^{e}
S-Metolachlor & Haloxyfop-p-ethyl	PRE & POST	800 & 350 ml acre $^{-1}$	11.14±0.09^{cd}	11.31±0.07^{cd}	1753.75±6.11^{e}	1895.51±6.31^{e}	3007.93±8.11^{e}	3303.71±5.20^{d}	4761.67±14.21^{e}	5199.22±9.88^{e}	36.83±0.02^{c}	36.46±0.07^{d}
Weed free	-	-	11.99±0.08^{a}	12.04±0.04^{a}	2085.29±6.43^{a}	2141.20±7.11^{a}	3165.11±7.22^{c}	3442.40±5.98^{a}	5250.41±11.43^{a}	5583.60±11.66^{a}	39.72±0.07^{a}	38.35±0.06^{a}
Weedy Check	-	-	9.42±0.11^{g}	9.73±0.05^{h}	923.36±5.50^{j}	891.31±4.62^{k}	2036.62±6.94^{j}	2013.35±6.32^{i}	2959.98±12.41^{i}	2904.67±9.52^{i}	31.19±0.06^{h}	30.69±0.10^{h}
Two hand hoeing	30 & 45 DAS	-	11.00±0.05^{de}	11.15±0.04^{de}	1750.32±6.95^{e}	1857.58±4.68^{f}	3255.36±7.24^{a}	3345.21±5.34^{c}	5005.68±12.54^{c}	5202.79±10.02^{e}	34.97±0.07^{g}	35.70±0.02^{g}
MS for treatment			1.46234**	1.42743**	251861**	322778**	354782**	522269**	1165693**	1652385**	12.2966**	10.8317**
LSD at 5%			0.1427	0.1921	18.582	18.951	18.857	18.548	35.438	34.686	0.1702	0.1861

2023 for fluazifop-p-butyl and 1518.95 kg·ha^{-1} in 2022 and 1635.42 kg·ha^{-1} in 2023 for Haloxyfop-p-ethyl. The sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl showed higher seed yield showing a substantial increase compared to sole pre-emergence applications. Similarly, two hand hoeing treatments showed seed yield comparable to pre-emergence herbicide applications with an average of 1750.32 kg·ha^{-1} in 2022 and 1857.58 kg·ha^{-1} in 2023. Furthermore, seed yield, treatments involving s-metolachlor + pendimethalin & fluazifop-p-butyl applied PRE & POST consistently outperformed than other herbicide treatments, yielding the highest values across both years. In 2022, this treatment yielded approximately a 100% increase in seed yield compared to the lowest performing herbicide treatment, fluazifop-p-butyl applied POST, and in 2023, it yielded approximately a 123% increase. Two hand hoeing at 30 & 45 DAS resulted in approximately a 90% increase in seed yield compared to the lowest herbicide treatment. While the pre-emergence application of s-metolachlor + pendimethalin showed harvest index of 36.12% in 2022 and 37.04% in 2023, showing an increase compared to other herbicide treatments. Similarly, the sequential application of s-metolachlor + pendimethalin with post-emergence herbicides like fluazifop-p-butyl or haloxyfop-p-ethyl demonstrated competitive harvest indices, indicating efficient resource allocation towards seed production. Pre-emergence application of s-metolachlor alone resulted in a slightly lower harvest index compared to combined treatments but still showed respectable values of 35.14% in 2022 and 35.68% in 2023. Post-emergence herbicide applications generally showed comparable harvest indices, with fluazifop-p-butyl showing 36.01% in 2022 and 35.92% in 2023, and haloxyfop-p-ethyl showing 35.28% in 2022 and 36.03% in 2023. Notably, weed-free conditions significantly boosted the harvest index, reaching 39.72% in 2022 and 38.35% in 2023 (Table 5).

The evaluation of protein content, oil content, and oil yield in soybeans during both 2022 and 2023, as outlined in Table 6 among the herbicides, the sequential application of s-metolachlor + pendimethalin and fluazifop-p-butyl applied pre-emergence and post-emergence showed competitive values of protein content and oil content. Specifically, this treatment combination showed higher protein content (35.78% in 2022 and 36.97% in 2023), oil content (20.33% in 2022 and 20.90% in 2023), and oil yield (386.96 kg·ha^{-1} in 2022 and 402.08 kg·ha^{-1} in 2023) compared to other herbicide treatments. while, haloxyfop-p-ethyl applied post-emergence showed relatively lower values for protein content (33.51% in 2022 and 34.16% in 2023), oil content (18.73% in 2022 and 18.35% in 2023) and oil yield (285.55 kg·ha^{-1} in 2022 and 298.03 kg ha^{-1} in 2023). Additionally, s-metolachlor + pendimethalin and fluazifop-p-butyl, as well as s-metolachlor +

Table 6. Effect of herbicide application time on protein content, oil content and oil yield of soybean

Treatments	Time of application	Dose	Protein content		Oil content		Oil yield Kg ha^{-1}	
			2022	2023	2022	2023	2022	2023
S-Metolachlor + Pendimethalin	PRE	900 ml acre^{-1}	34.68±0.06^{d}	35.77±0.12^{e}	18.88±0.06^{f}	18.92±0.03^{g}	308.85±1.04^{f}	335.71±1.39^{f}
S-Metolachlor	PRE	800 ml acre^{-1}	34.26±0.07^{e}	35.40±0.13^{f}	18.57±0.05^{g}	18.76±0.04^{g}	297.45±1.80^{g}	320.00±1.98^{g}
Fluazifop-p-butyl	POST	800 ml acre^{-1}	33.26±0.07^{f}	34.89±0.06^{g}	18.34±0.08^{h}	18.53±0.05^{h}	288.56±1.13^{h}	304.88±1.58^{h}
Haloxyfop-p-ethyl	POST	350 ml acre^{-1}	32.86±0.08^{g}	34.16±0.08^{h}	18.11±0.06^{i}	18.35±0.05^{h}	273.07±0.51^{i}	298.03±0.13^{i}
S-Metolachlor + Pendimethalin & Fluazifop-p-butyl	PRE & POST	900 & 800 ml acre^{-1}	35.86±0.06^{b}	36.97±0.04^{b}	20.23±0.07^{b}	20.33±0.04^{b}	371.53±0.13^{b}	402.08±1.88^{b}
S-Metolachlor + Pendimethalin & Haloxyfop-p-ethyl	PRE & POST	900 & 350 ml acre^{-1}	35.69±0.07^{b}	36.56±0.08^{c}	19.88±0.05^{c}	20.11±0.06^{c}	356.80±1.36^{c}	392.99±2.28^{c}
S-Metolachlor & Fluazifop-p-butyl	PRE & POST	800 & 800 ml acre^{-1}	35.36±0.08^{c}	36.26±0.08^{d}	19.34±0.07^{e}	19.56±0.10^{e}	343.07±1.43^{d}	374.46±3.16^{d}
S-Metolachlor & Haloxyfop-p-ethyl	PRE & POST	800 & 350 ml acre^{-1}	35.15±0.07^{c}	36.13±0.07^{d}	19.16±0.06^{e}	19.32±0.06^{f}	334.04±0.99^{e}	364.15±1.97^{e}
Weed free	-	-	37.15±0.08^{a}	37.73±0.09^{a}	20.74±0.08^{a}	20.90±0.06^{a}	430.56±2.41^{a}	445.46±2.37^{a}
Weedy check	-	-	31.37±0.09^{h}	32.50±0.10^{i}	17.22±0.06^{j}	17.73±0.10^{i}	156.97±0.80^{j}	156.07±0.97^{j}
Two hand hoeing	30 & 45 DAS	-	34.86±0.08^{d}	35.86±0.09^{e}	19.66±0.06^{d}	19.76±0.05^{d}	342.17±1.99^{d}	364.97±0.79^{e}
MS for treatment			7.69014**	6.09742**	3.11852**	2.68537**	14349.2**	17216.9**
LSD at 5%			0.2144	0.2609	0.1936	0.1820	4.1353	5.7296

pendimethalin and haloxyfop-p-ethyl showed notable performance comparable to the above combination. Furthermore, two hand hoeing treatment showed similar to certain herbicide treatments, with protein content averaging at 34.86% in 2022 and 35.86% in 2023, oil content averaging at 19.66% in 2022 and 19.76% in 2023 and oil yield averaging at 342.17 kg ha^{-1} in 2022 and 364.97 kg ha^{-1} in 2023.

WCP showed various trends influenced by herbicide application timing and types during both 2022 and 2023. The sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl demonstrated the highest weed control percentages ranging from approximately 44.59% to 75.65% at 45 days after sowing (DAS). While, sole post-emergence herbicides fluazifop-p-butyl and haloxyfop-p-ethyl showed lower WCP ranging from approximately 33.09% to 44.08% at 45 DAS. Notably, the weed-free condition consistently achieved 100% weed control across all intervals, while the weedy check showed negative percentages indicating increased weed infestation. Two hand hoeing treatments displayed moderate WCP ranging from approximately 31.38% to 61.28%

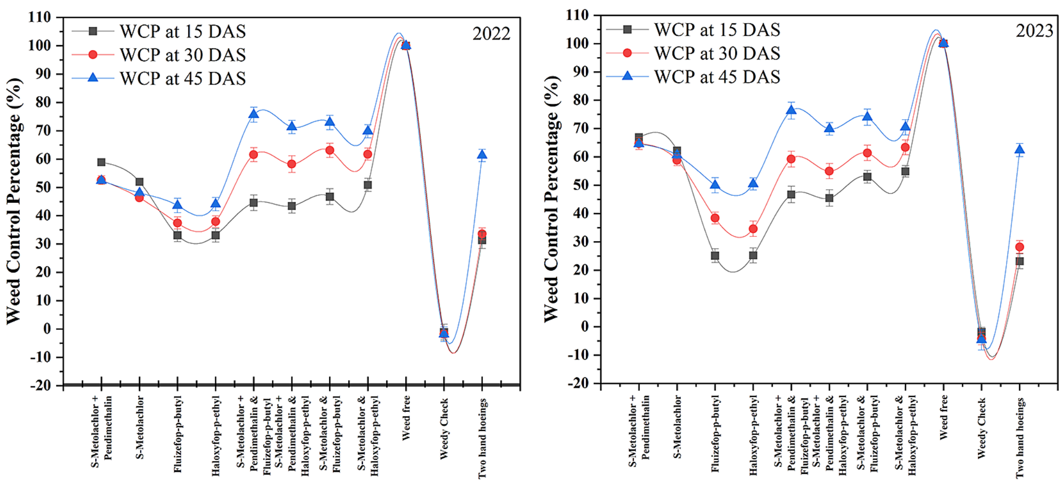


Figure 4. Effectiveness of weed control strategies measured by weed control percentage (WCP) at different growth stages in 2022 and 2023

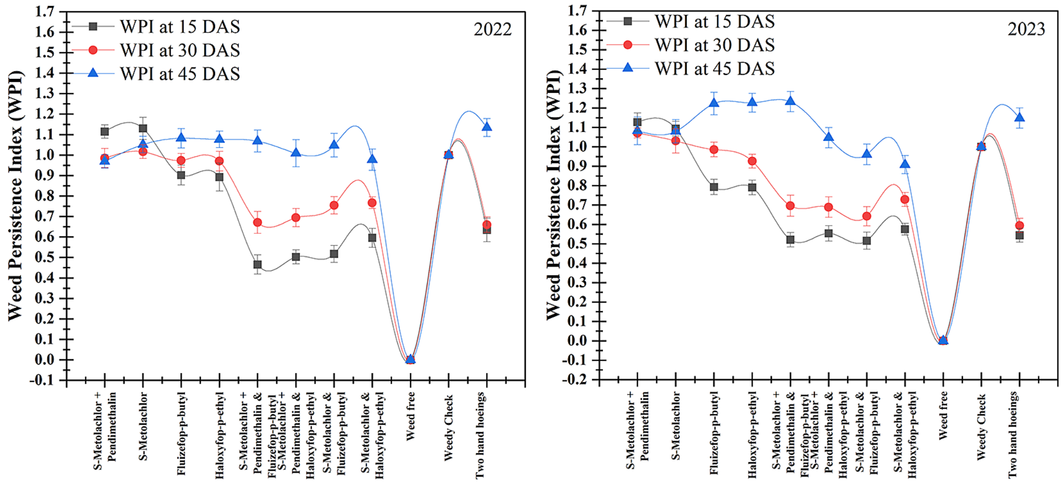


Figure 5. Effectiveness of weed control strategies measured by weed persistence index (WPI) at different growth stages in 2022 and 2023

at 45 DAS showing their effectiveness in controlling weeds but with lower efficacy compared to certain herbicide treatments (Fig. 4). Similarly, WPI in soybeans for both 2022 and 2023, as depicted in Figure 5, that pre-emergence herbicide including s-metolachlor + pendimethalin and s-metolachlor alone, consistently showed higher WPI values compared to post-emergence applications, showing better persistence in weed control. Specifically, pre-emergence treatments in 2023 demonstrated WPI values ranging from approximately 1.071 to 1.127 at 15 DAS, while those in 2022 ranged from approximately 0.969 to 1.130. In contrast, post-emergence herbicides fluazifop-p-butyl and haloxyfop-p-ethyl displayed lower WPI values, ranging from approximately 0.790 to 1.227 at 15 DAS in 2023 and from approximately 0.893 to 1.082 in 2022 showing a reduced ability to maintain weed control over time. Notably, the weed-free condition consistently achieved a WPI of 0.000 across all intervals in both years indicating complete weed suppression, while the weedy check consistently scored a WPI of 1.000, indicating no weed control. Two hand hoeing treatments showed moderate WPI values, ranging from approximately 0.544 to 1.148 at 45 DAS in 2023 and from approximately 0.634 to 1.134 in 2022, indicating effective but less persistent weed control compared to certain herbicide treatments.

While evaluation of WCE, WI, WMI, and AMI, HEI in soybeans across both 2022 and 2023, as depicted in Figure 6, 7, 8, 9, and 10, highlights the varied impacts of herbicide application timing and types on weed and agronomic management. The sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl or haloxyfop-p-ethyl showed the highest WCE and HEI during both years, indicating their effectiveness in weed and herbicide management. S-metolachlor + pendimethalin & fluazifop-p-butyl (PRE & POST) in 2022 had WCE of 88.62%, WI of 11.43%, HEI of 8.83, WMI of 1.13, and AMI of 0.38, while in 2023, it displayed WCE of 89.16%, WI of 7.19%, HEI of 11.38, WMI of 1.38, and AMI of 0.38.

While in sole application of pre-emergence herbicide notably s-metolachlor + pendimethalin and s-metolachlor alone generally showed higher WCE and lower WI compared to post-emergence applications showing better weed control efficiency and reduced weed indices. Specifically, pre-emergence treatments consistently showed WCE values ranging from approximately 46.41% to 54.68% in 2022 and from 59.40% to 63.44% in 2023, with corresponding WI values ranging from approximately 16.64 to 22.67 in 2022 and from 16.64 to 19.84 in 2023. S-metolachlor + pendimethalin (PRE) in 2022 showed WCE of 54.68%, WI of 21.04%, HEI of 1.73, WMI of 1.43, and AMI of 0.43, while in 2023, it showed WCE of 63.44%, WI of 16.64%, HEI of 2.74, WMI of 1.58, and AMI of 0.58. Conversely, post-emergence herbicides like fluazifop-p-butyl and haloxyfop-p-ethyl displayed relatively lower WCE values and higher WI values. In 2022, fluazifop-p-butyl (POST) had WCE of 40.08%, WI of 24.02%, HEI of 1.20, WMI of 1.79, and AMI of 0.79, while in 2023, it showed WCE of 50.40%, WI of 22.63%, HEI of 1.73, WMI of 1.70, and AMI of 0.70.

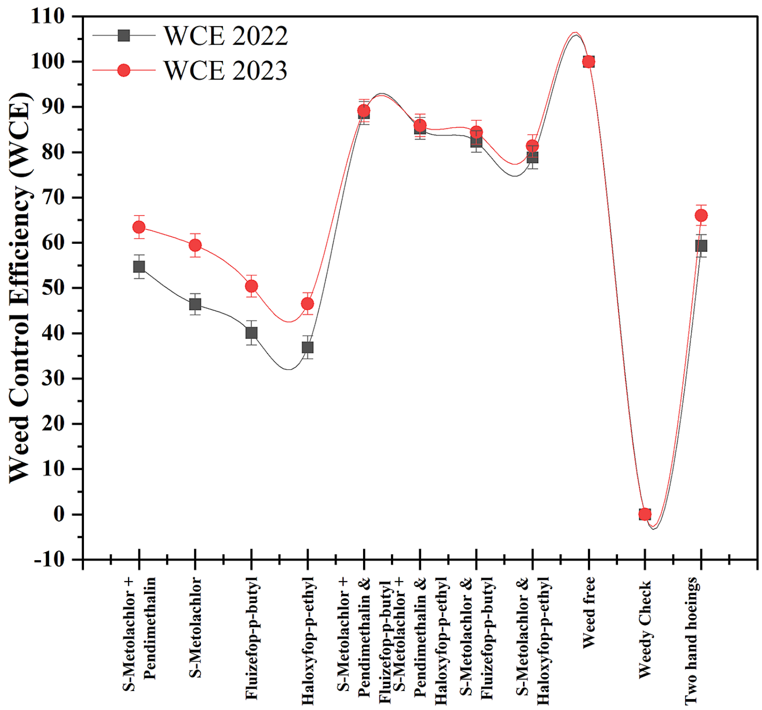


Figure 6. Effectiveness of weed control strategies measured by weed control efficiency (WCE) in 2022 and 2023

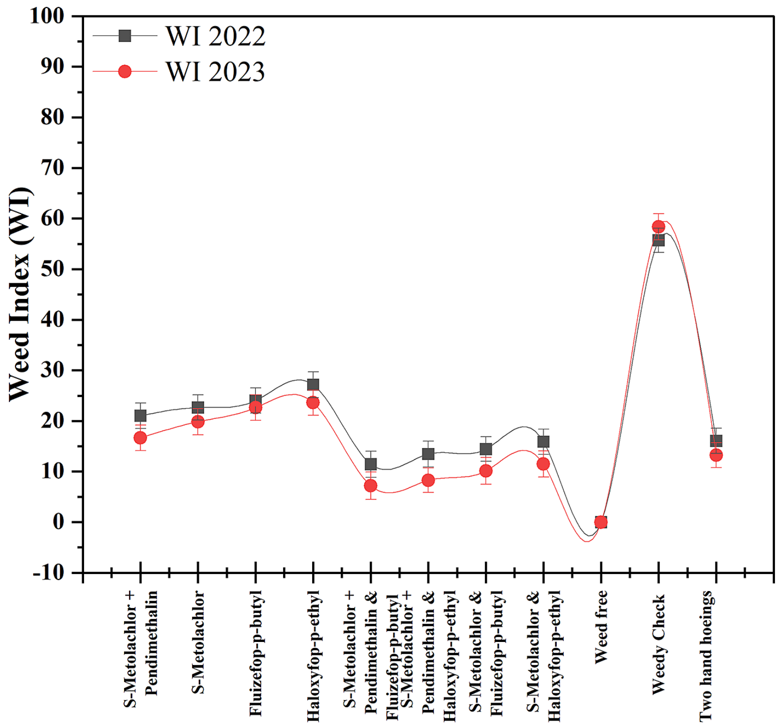


Figure 7. Effectiveness of weed control strategies measured by weed index (WI) in 2022 and 2023

Haloxyfop-p-ethyl (POST) in 2022 showed WCE of 36.87%, WI of 27.16%, HEI of 1.02, WMI of 1.75, and AMI of 0.75, while in 2023, it exhibited WCE of 46.51%, WI of 23.62%, HEI of 1.56, WMI of 1.80, and AMI of 0.80. However, it was worth noting that two hand hoeing treatments displayed competitive WCE and AMI, underscoring their potential role in integrated weed management strategies. Two hand hoeing (30 & 45 DAS) in 2022 showed WCE of 59.29%, WI of 16.06%, HEI of 2.20, WMI of 1.51, and AMI of 0.51, while in 2023, it showed WCE of 66.03%,

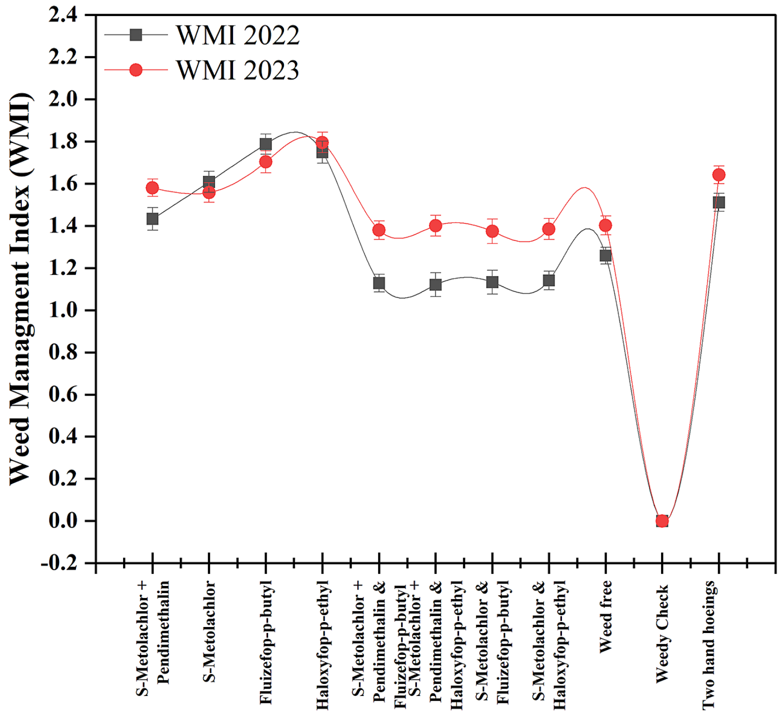


Figure 8. Effectiveness of weed control strategies measured by weed management index (WMI) in 2022 and 2023

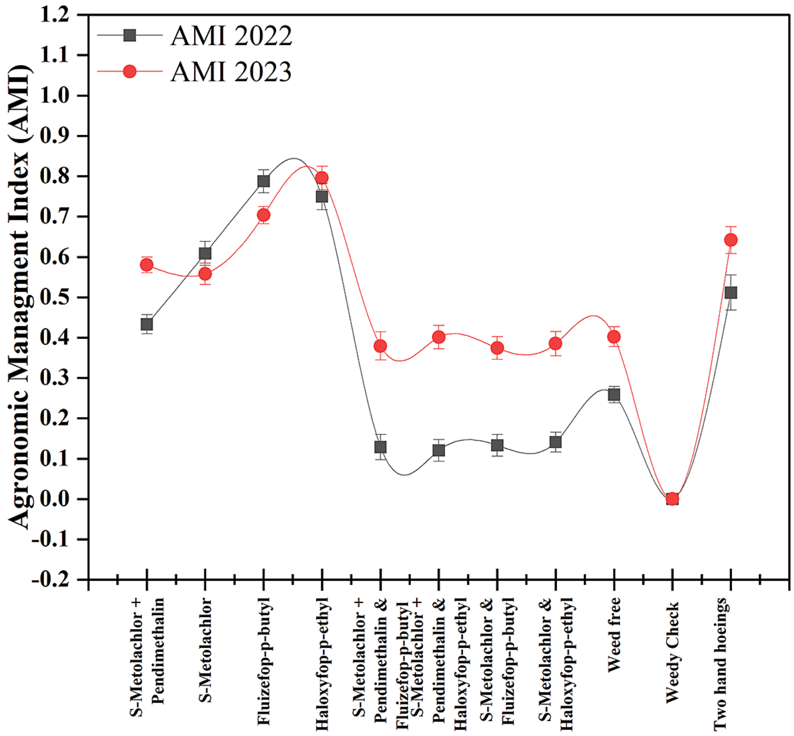


Figure 9. Effectiveness of weed control strategies measured by agronomic management index (AMI) in 2022 and 2023

WI of 13.25%, HEI of 3.19, WMI of 1.64, and AMI of 0.64. The Chord diagrams in Figure 11 for the years 2022 and 2023 illustrate the intricate relationships between various weed attributes and soybean growth, yield, and quality parameters under different herbicide application timings. The diagrams depict strong connections between the sequential application of s-metolachlor + pendimethalin (PRE) followed by fluazifop-p-butyl (POST) (T5) and key growth parameters such as crop growth rate (CGR), leaf area index (LAI), and cumulative leaf area duration (C-LAD). This

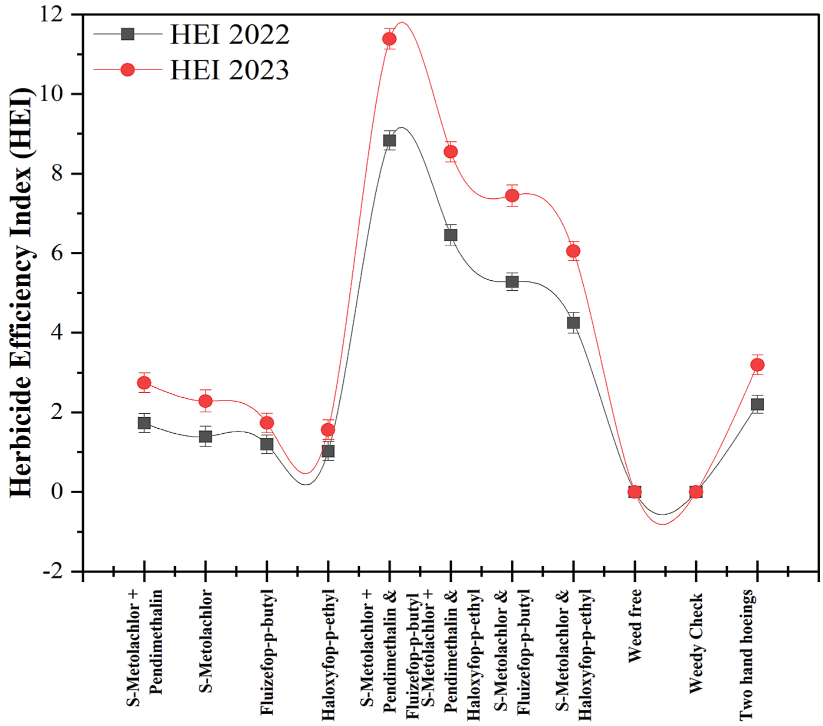
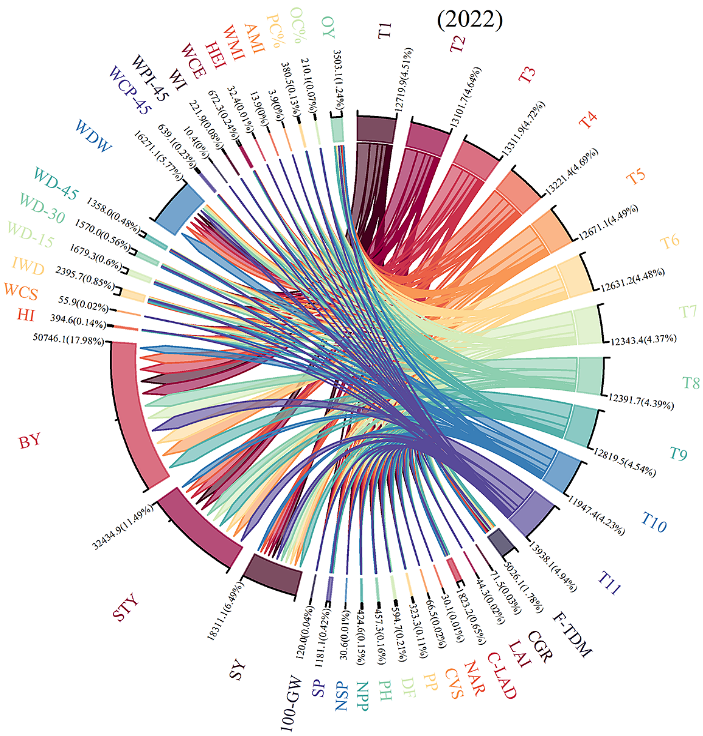


Figure 10. Effectiveness of weed control strategies measured by herbicide efficiency index (HEI) in 2022 and 2023

treatment also shows a significant reduction in weed density at 15, 30, and 45 days after spray, as well as improvements in seed yield (SY), stover yield (STY), and biological yield (BY). These results showed the importance of sequential application of pre and post-emergence herbicides are crucial for higher soybean growth, quality, yield and effective weed management.

The Pearson Correlation (Fig. 12) showed the relationship between weeds parameters and soybean growth, yield and quality parameters under pre and post emergence herbicide applications. Soybean yield and other growth attributes including total dry matter, crop growth rate, leaf area index and cumulative leaf area duration showed as dark red which is strong positive correlations in both years which mean the effective weed management for higher soybean productivity. Whereas the weeds attributes including weeds density at different intervals and weed dry weight showed dark blue which mean the strong negative correlations between soybean yield and yield components. It suggested that increased weed densities have bad impact on soybean growth yield and quality. While the weed control efficiency and herbicide efficiency index showed positive correlation with yield attributes which highlight the importance of timely application herbicide in weed management for enhancing crop yield. On the other hand, quality parameters including protein content and oil content showed positive correlation with growth parameters and negative correlation with weed attributes which mean effective weed management not only enhance the yield of soybean it also improved the quality of soybean. This correlation showed the role of integrated weed management for enhancing soybean growth, quality and yield.

The clustered heatmap (Fig. 13) showed visual representation of relationship between weed parameters and soybean growth, yield and quality parameters during both years. In heatmap different colour intensities with different cells showed the degree of association between different parameters. Weed free and weedy check clusters clearly showed their impact on weed parameters and soybean growth yield and quality. The application of sole s-metolachlor + pendimethalin (T1) and in sequential application with post emergence herbicides (T5 and T6) showed significant effect on growth parameters including leaf area index, net assimilation rate and crop vigor score which is presented by the darker colors. Higher weed control percentage and lower weed densities at different intervals were strongly correlated with each other. Whereas the sole application of post emergence herbicides (T3 and T4) and hand hoeing (T11) showed various effects and have different impacts on weed control and soybean



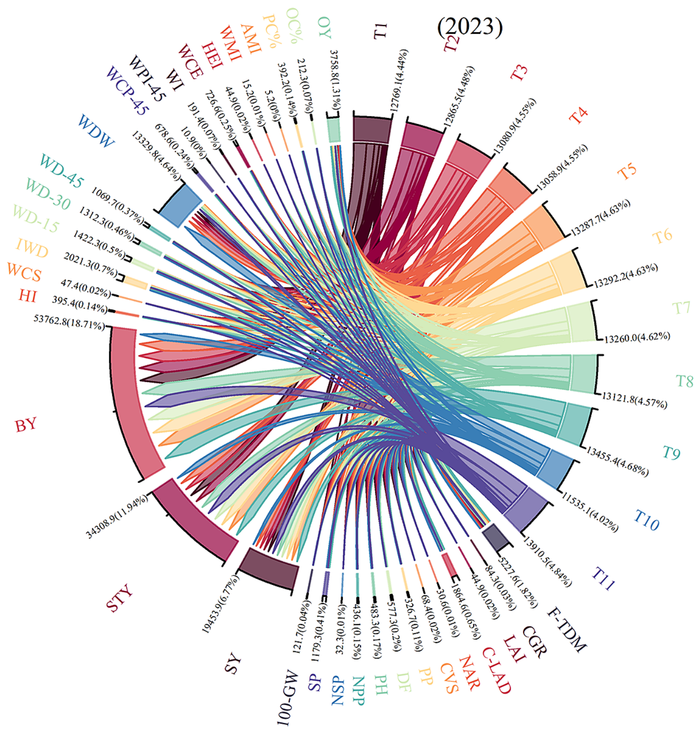


Figure 11. Chord diagram of weeds attributes and soybean growth, yield, and quality parameters under different herbicides time of application during 2022 and 2023. F-TDM (final total dry matter), CGR (crop growth rate), LAI (leaf area index) C-LAD (commutative leaf area duration), NAR (net assimilation rate), CVS (crop vigor score), PP (plant population) DF (days to flowering), PH (plant height), NPP (number of pods per plant), NSP (number of seeds per pod), SP (number of seeds per plant), 100-GW (100 grains weight) SY (seed yield) STY (stover yield) BY (biological yield) HI (harvest index), WCS (weed cover score), IWD (initial weed density),WD-15 (weeds density after 15 days of spray), WD-30 (weeds density after 30 days of spray), WD-45 (weeds density after 45 days of spray), WDW (weeds dry weight), WCP-45 (weed control percentage at 45-das), WPI-45 (weed persistence index at 45-das), WI (weed index), WCE (weed control efficiency), HEI (herbicide efficiency index), WMI (weed management index), AMI (agronomic management index), PC (protein content), OC (oil content), OY (oil yield). Whereas, T1 (S-Metolachlor + Pendimethalin-PRE), T2 (S-Metolachlor-PRE), T3 (Fluazifop-p-butyl-POST), T4 (Haloxyfop-p-ethyl-POST), T5 (S-Metolachlor + Pendimethalin-PRE & Fluazifop-p-butyl- POST), T6 (S-Metolachlor + Pendimethalin-PRE & Haloxyfop-p-ethyl- POST), T7 (S-Metolachlor-PRE & Fluazifop-p-butyl-POST), T8 (S-Metolachlor-PRE & Haloxyfop-p-ethyl-POST), T9 (Weed free), T10 (Weedy Check), T11 (Two hand hoeing)

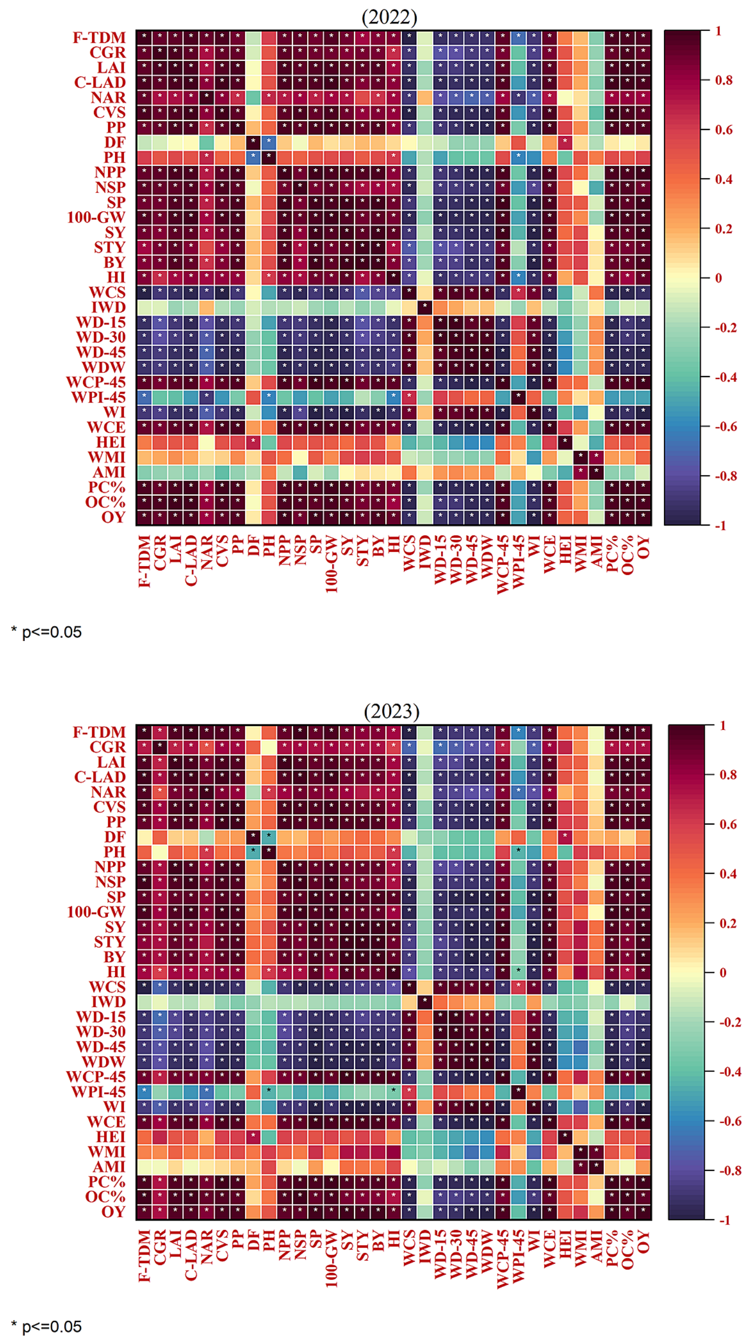


Figure 12. Pearson correlation of weeds attributes and soybean growth, yield, and quality parameters under different herbicides time of application during 2022 and 2023. F-TDM (final total dry matter), CGR (crop growth rate), LAI (leaf area index) C-LAD (commutative leaf area duration), NAR (net assimilation rate), CVS (crop vigor score), PP (plant population) DF (days to flowering), PH (plant height), NPP (number of pods per plant), NSP (number of seeds per pod), SP (number of seeds per plant), 100-GW (100 grains weight) SY (seed yield) STY (stover yield) BY (biological yield) HI (harvest index), WCS (weed cover score), IWD (initial weed density),WD-15 (weeds density after 15 days of spray), WD-30 (weeds density after 30 days of spray), WD-45 (weeds density after 45 days of spray), WDW (weeds dry weight), WCP-45 (weed control percentage at 45-das), WPI-45 (weed persistence index at 45 -das), WI (weed index), WCE (weed control efficiency), HEI (herbicide efficiency index), WMI (weed management index), AMI (agronomic management index), PC (protein content), OC (oil content), OY (oil yield)

growth. The different pattern of heatmap showed the importance of sequential application of herbicides for higher soybean growth, quality and yield. The Principal component analysis (Fig. 14) showed the visual representation of relationship between weeds and soybean growth, yield and quality parameters during 2022 and 2023. In both years, the PC1 showed the majority of variance 84.3% and 83.3% in 2022 and 2023 respectively, while the PC2 contribute in smaller portion which in 7.4%

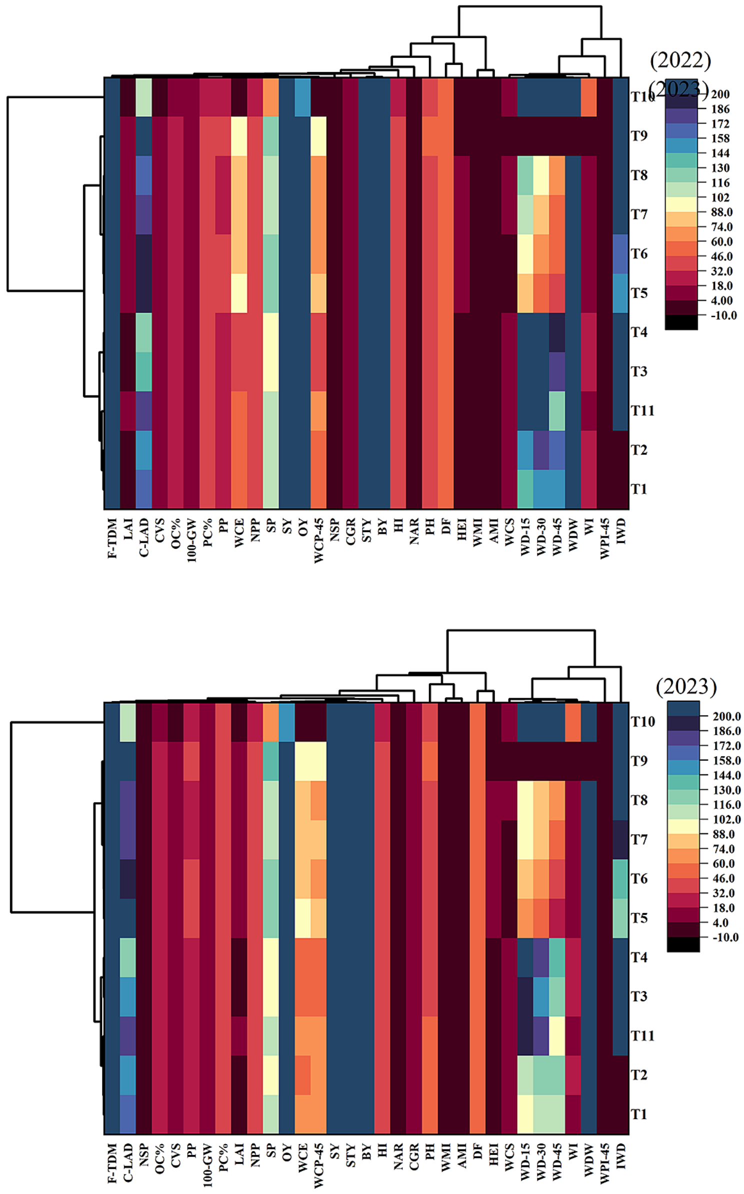


Figure. 13. Clustered heatmap of weeds attributes and soybean growth, yield, and quality parameters under different herbicides time of application during 2022 and 2023. F-TDM (final total dry matter), CGR (crop growth rate), LAI (leaf area index) C-LAD (commutative leaf area duration), NAR (net assimilation rate), CVS (crop vigor score), PP (plant population) DF (days to flowering), PH (plant height), NPP (number of pods per plant), NSP (number of seeds per pod), SP (number of seeds per plant), 100-GW (100 grains weight) SY (seed yield) STY (stover yield) BY (biological yield) HI (harvest index), WCS (weed cover score), IWD (initial weed density),WD-15 (weeds density after 15 days of spray), WD-30 (weeds density after 30 days of spray), WD-45 (weeds density after 45 days of spray), WDW (weeds dry weight), WCP-45 (weed control percentage at 45-das), WPI-45 (weed persistence index at 45 -das), WI (weed index), WCE (weed control efficiency), HEI (herbicide efficiency index), WMI (weed management index), AMI (agronomic management index), PC (protein content), OC (oil content), OY (oil yield). Whereas, T1 (S-Metolachlor + Pendimethalin-PRE), T2 (S-Metolachlor-PRE), T3 (Fluazifop-p-butyl-POST), T4 (Haloxyfop-p-ethyl-POST), T5 (S-Metolachlor + Pendimethalin-PRE & Fluazifop-p-butyl- POST), T6 (S-Metolachlor + Pendimethalin-PRE & Haloxyfop-p-ethyl- POST), T7 (S-Metolachlor-PRE & Fluazifop-p-butyl-POST), T8 (S-Metolachlor-PRE & Haloxyfop-p-ethyl-POST), T9 (Weed free), T10 (Weedy Check), T11 (Two hand hoeing)

in both years. All the important growth and yield parameters including total dry matter, crop growth rate, leaf area index and seed yield were clustered and showed the strong positive correlation and linked with s-metolachlor & fluazifop-p-butyl (T7), s-metolachlor & haloxyfop-p-ethyl (T8) and weed free (T9). Whereas the s-metolachlor + pendimethalin (T1), s-metolachlor (T2) and fluazifop-p-butyl (T3) were linked with lower weed control parameters including weeds density and weeds dry weight which means less effective weed control. The higher growth and yield parmetrs are linked

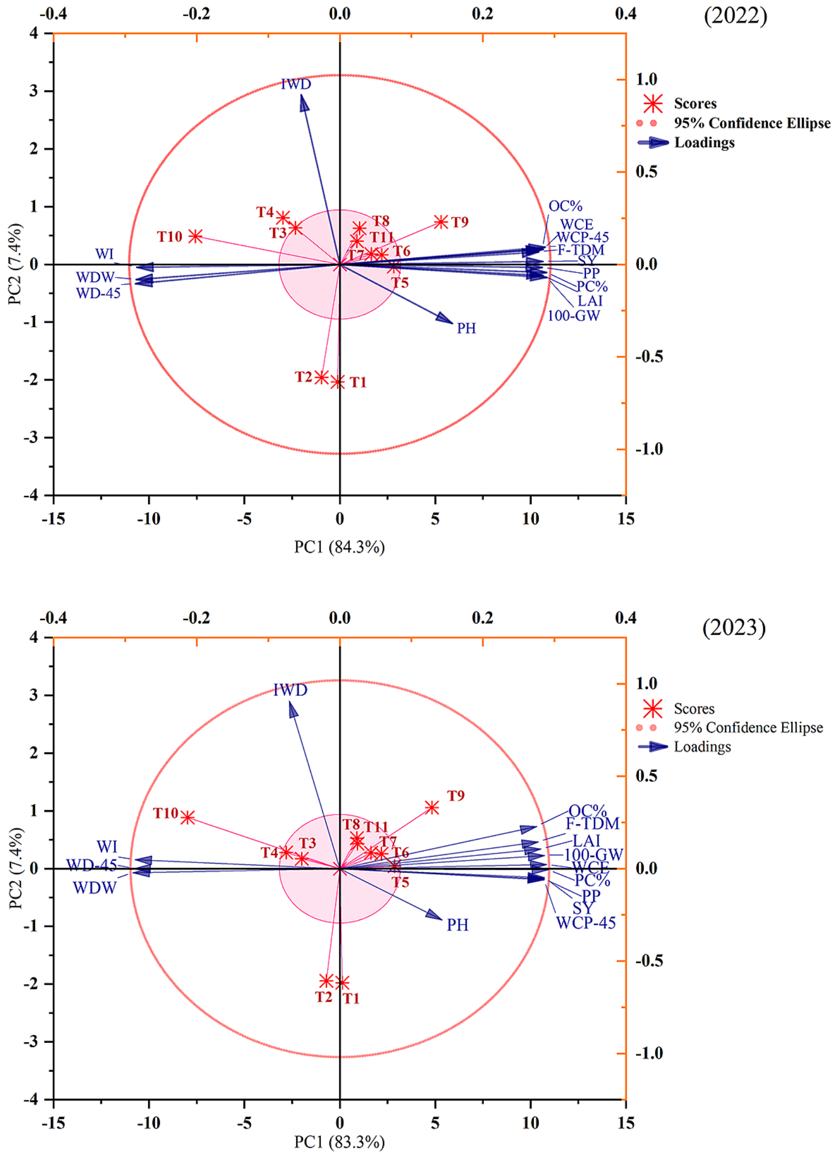


Figure 14. Principal component analysis (PCA) of weeds attributes and soybean growth, yield, and quality parameters under different herbicides time of application during 2022 and 2023. F-TDM (final total dry matter), CGR (crop growth rate), LAI (leaf area index) C-LAD (commutative leaf area duration), NAR (net assimilation rate), CVS (crop vigor score), PP (plant population) DF (days to flowering), PH (plant height), NPP (number of pods per plant), NSP (number of seeds per pod), SP (number of seeds per plant), 100-GW (100 grains weight) SY (seed yield) STY (stover yield) BY (biological yield) HI (harvest index), WCS (weed cover score), IWD (initial weed density),WD-15 (weeds density after 15 days of spray), WD-30 (weeds density after 30 days of spray), WD-45 (weeds density after 45 days of spray), WDW (weeds dry weight), WCP-45 (weed control percentage at 45-das), WPI-45 (weed persistence index at 45 -das), WI (weed index), WCE (weed control efficiency), HEI (herbicide efficiency index), WMI (weed management index), AMI (agronomic management index), PC (protein content), OC (oil content), OY (oil yield). Whereas, T1 (S-Metolachlor + Pendimethalin-PRE), T2 (S-Metolachlor-PRE), T3 (Fluazifop-p-butyl-POST), T4 (Haloxyfop-p-ethyl-POST), T5 (S-Metolachlor + Pendimethalin-PRE & Fluazifop-p-butyl-POST), T6 (S-Metolachlor + Pendimethalin-PRE & Haloxyfop-p-ethyl- POST), T7 (S-Metolachlor-PRE & Fluazifop-p-butyl-POST), T8 (S-Metolachlor-PRE & Haloxyfop-p-ethyl-POST), T9 (Weed free), T10 (Weedy Check), T11 (Two hand hoeing)

with weed free (T9) treatment which shows effective weed control. The biplot showed the clear difference between effective herbicide treatments and their effects on soybean parameters in which well managed treatment showed the higher yield and quality attributes compared to poorly weed control like weedy check.

DISCUSSION

The research findings found from the two-year study on pre and post emergence herbicides and two hand hoeing for effective weed control and higher soybean growth, yield and quality. These herbicides treatments showed clearly impact on weed infestation among different weed species and soybean growth, yield and quality. During both years, there was different level of infestation of broadleaf weeds, grasses and sedges. This variation showed the dynamic nature of weed population and their response to both environmental circumstances and management strategies. *Tribulus terrestris* L. had high infestation levels among broadleaf weeds and showed higher competitive adaptability and capacity to compete in soybean fields (Menalled et al., 2001). *Convolvulus arvensis* L. showed a comparable increase in infestation from moderate to high, showing the challenges which weed species poses. On the other hand, several species such as *Parthenium hysterophorus* L. and *Xanthium strumarium* L., maintained minimal to undetectable infection levels, showing their vulnerability to control measures. Regarding grasses, *Cynodon dactylon* L. showed a significant increase in infestation levels, showed the need for efficient grass weed control methods. On the other hand, low infestation levels of *Phalaris minor* Retz. and *Paspalum distichum* (L) showed their minimal effect on soybean productivity (Singh et al., 2014b). *Cyperus difformis* showed a notable rise in infestation among sedges, highlighting the difficulties in managing sedge weeds in soybean fields. Daramola et al. (2019) reported that rainfall has a major impact on the distribution of weed species and their degree of competition within a weed community.

The weed cover scores, weed density and weed dry weight were significantly reduced by sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl herbicides. These results were in line with previous studies showed the effectiveness of integrated weed management approaches combining pre and post-emergence herbicides for reducing weed competition and higher soybean growth (Daramola, 2020; Singh et al., 2014b). The sequential application of pre-emergence and post-emergence herbicide showed that pre-emergence herbicides target weed seeds before germination which prevent weeds germination which leads to lower competition with soybean (Ezebuiro et al., 2021; Rupareliya et al., 2020). For preventing weed seed germination and early weed growth the s-metolachlor and pendimethalin were used as pre emergence herbicides. S-metolachlor inhibits the cell division and elongation that target the long chain fatty acids synthesis which are very important for the integrity of cell membrane of seedlings. Whereas the pendimethalin acted as inhibition of microtubule formation which is important cell division which leads to prevent the weed growth and seedling (Walsh et al., 2004). When the s-metolachlor + pendimethalin were applied in combination they target the synthesis of fatty acid and cell division process which provide comprehensive control of broad spectrum weeds. This dual action effectively prevents the weed seedling from emergence which reduced the competition for the resources with soybean plant. It was showed that the s-metolachlor with pendimethalin effectively reduced the weed density and biomass leads to higher soybean yield (Sirisha et al., 2020). Post emergence herbicides target the specific component Photosystem II to effect the photosynthesis system of weed plant in which it disturbs the flow of electrons and evolution of oxygen which reduced the ATPs which are important for biochemical reactions. It also disturbs the mitochondria and chloroplast by inhibiting the oxidative and photophosphorylation pathways which effect the photosynthesis and respiration system of weeds (Meloni et al., 2022). On the other hand, post emergence herbicide fluazifop-p-butyl target the grass weeds by inhibiting the enzyme acetyl-CoA carboxylase (ACCase) which are important for biosynthesis of fatty acid. This inhibition disturbs the production of lipid which are important for the formation of cell membrane and cause of wilting, chlorosis and necrosis in treated plants which leads to weed death (Luo and Matsumoto, 2002; Dias et al., 2017). Hand hoeing was also effective weed control and good alternative to chemical weed control especially when applied at critical growth stage in soybean (Gohil, 2015; Patil et al., 2019). The WCP, WPI, WCE, WI, HEI, WMI and AMI also support the effectiveness of the herbicides treatment in soybean field. The higher WCP, WPI, WCE and lower WI was showed in pre-emergence herbicides as compared to the post emergence herbicides which means pre emergence showed good weed control (Singh et al., 2014b). While the sequential application of s-metolachlor + pendimethalin as pre then fluazifop-p-butyl as post showed the highest WCP, WPI, WCE, HEI and lowest WI showing their higher effectiveness on weed germination and their growth throughout the season (Singh et al., 2014a). So, the sequential application of herbicides increased the weed suppression and reduced the development of herbicide resistant weed in soybean field (Das et al., 2016). Additionally, the good WCE and AMI showed that hand hoeing was also the best alternative of herbicides weed management to control the weeds in soybean field (Singh et al., 2018; Kumar et al., 2019).

Growth parameters such as crop vigor score, total dry matter (TDM), leaf area index (LAI), and crop growth rate (CGR), leaf area duration (LAD), and net assimilation rate (NAR) were recorded higher where sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl herbicides were applied during both years (Daramola, 2020). S-metolachlor inhibit the long-chain fatty acid synthesis while pendimethalin inhibits microtubule formation both effectively minimize weed competition during critical growth stages in soybean (Ghadiya et al., 2024). Whereas fluazifop-p-butyl targeted ACCase in grass weeds which disturbs fatty acid biosynthesis then leads to weed death and crop has uninterrupted access to resources (Rani and Venkateswarlu, 2021). This sequential application enhanced LAI and LAD which mean providing greater photosynthetic area to crop plant leading to higher crop growth rate and total dry matter. Good weed management practices improve the net assimilation rate by reducing competition allowing plant to assimilate nutrients more efficiently and higher growth rate (Hamza and Soliman, 2011). These results showed that sequential application of pre and post-emergence herbicides can effectively suppress weed competition and increase soybean vigor. While the sole application of post-emergence herbicides showed lower vigor scores which means limited efficacy in weed control and crop growth (Khaliq et al., 2012). The cumulative LAD showed the consistent impact of herbicide on soybean leaf area development. The sequential application of s-metolachlor + pendimethalin and fluazifop-p-butyl applied pre and post-emergence showed longer leaf area development resulted higher LAD compared with sole application of pre or post-emergence herbicides. Hand hoeing also showed comparable effectiveness in enhancing leaf area development which is a good alternative practice of weed management (Ezebuiro et al., 2021). The results of NAR showed the positive effects of herbicide applications on soybean assimilation rates. Sequential application of s-metolachlor + pendimethalin with fluazifop-p-butyl continuously showed higher NAR which means their effectiveness enhancing assimilation rates and soybean crop growth (Ezebuiro et al., 2021b). While the sole application of post-emergence herbicides and weedy check treatment showed lower assimilation rates highlighting the unfavorable effects of weed competition on soybean productivity. The application timing of herbicides has the significant effects on leaf area index of soybean plant. The treatments in which both the pre emergence herbicide then post emergence herbicide were applied they showed the early leaf area development which present their effectiveness for reducing weed crop competition and enhancing the soybean growth. While post emergence herbicides showed slower leaf area expansion which means their limited efficacy in early weed management (Rupareliya et al., 2020). Whereas the total dry matter accumulation further showed importance of sequential application of herbicides in enhancing soybean biomass production. The application of s-metolachlor + pendimethalin with fluazifop-p-butyl showed high total dry matter which means these treatments were best suited for the weed control and soybean growth and biomass accumulation. While the sole application of post emergence herbicides showed lower total dry matter which means this treatment was not good in early weed control which leads to the lower biomass accumulation (Rupareliya et al., 2020).

Regarding soybean yield attributes the sequential application of pre-emergence s-metolachlor + pendimethalin with post-emergence fluazifop-p-butyl herbicides achieved significantly higher plant population, days to flowering, plant height, number of pods plant $^{-1}$, number of seeds pod^{-1}, number of seeds plant^{-1}, 100 grain weight, seed yield, stover yield, biological yield and harvest index (%) (Kadam et al., 2018). The sequential application of pre-emergence herbicides s-metolachlor and pendimethalin followed by post-emergence fluazifop-p-butyl showed higher plant population, days to flowering, plant height, number of pods per plant, number of seeds per pod, number of seeds per plant, 100 grain weight, seed yield, stover yield, biological yield, and harvest index by sustained weed control throughout the growing season (Sandil et al., 2015; Harithavardhini et al., 2017; Ezebuiro et al., 2021a). S-metolachlor inhibits synthesis of long-chain fatty acid and preventing cell membrane formation in emerging weed seedlings while the pendimethalin inhibits microtubule formation and blocked the cell division. These pre-emergence herbicides reduce early weed competition and produced higher plant populations and more uniform crop establishment. Fluazifop-p-butyl targets ACCase in grass weeds and disturb fatty acid biosynthesis leading to weed plant death. This comprehensive weed management allows crops uninterrupted access to obtain essential resources such as nutrients, light, and water. The lower weed competition produced the less biotic stress which leads to more efficient utilization of available resources (Aher et al., 2023). This results in better vegetative growth showed increased plant height and earlier flowering. The enhanced growth conditions promote the development of more pods per plant and seeds per pod as the plants can allocate more energy to reproductive structures. The more nutrient uptake and more optimal growing conditions produced heavier grains which resulted to higher 100 grain weight. While the combined effect of these factors produced higher seed yield, stover yield and overall biological yield (Muttanna, 2015; Nishant, 2018). The improved harvest index showed more proportion of the plant biomass which converted into harvestable product showing the efficacy of sequential herbicide application for producing higher crop productivity (Hamza and Soliman, 2011; Jakhar and Sharma, 2015; Rohit and Narayan, 2018; Rani and Venkateswarlu, 2021; Ghadiya et al., 2024).

The evaluation quality parameters including protein content, oil content, and oil yield in soybean under different herbicide treatments showed the physiological responses of the crop to herbicide application timing and types. The sequential application of s-metolachlor + pendimethalin as pre-emergence with fluazifop-p-butyl showed significantly higher protein content, oil content and oil yield in soybean can be attributed to several scientific principles. When sequential application of pre-emergence herbicide with post-emergence herbicides were applied they targeted the weed species at different growth stages by providing more effective weed control throughout the cropping season. This integrated approach reduces competition between weeds and soybean plants for essential resources such as water, nutrients, and sunlight by promoting optimal growth and development of soybean plants (Rupareliya et al., 2020; Ezebuiro et al., 2021). Good weed control reduced stress on soybean plants and allow them to obtain more resources for the synthesis of proteins and oils in the seeds which resulted in higher protein content, oil content, and oil yield. Other one is the herbicide application timing can affect the physiological processes related to protein and oil accumulation in soybean seeds. Pre-emergence herbicides applied before weed emergence which prevent early competition for resources and allow soybean plants to establish a stronger root system and canopy architecture which are important for efficient nutrient uptake and photosynthesis (Ezebuiro et al., 2021). This early weed control produced higher protein and oil accumulation during seed development stages which increased protein content, oil content and oil yield in mature soybean seeds. Whereas post-emergence herbicides applied after weed emergence may cause stress on soybean plants particularly if weeds have already established significant competition. Stress from herbicide application can disrupt physiological processes such as photosynthesis, nutrient uptake and hormone signaling pathways, potentially leading to reduced seed quality and yield (Rupareliya et al., 2020). The lower protein content, oil content and oil yield observed under post-emergence herbicide treatments like haloxyfop-p-ethyl can be adverse effects of herbicide-induced stress on soybean metabolism and productivity.

The study showed the importance of sequential application of pre and post-emergence herbicides to optimize weed control, crop yield and quality in soybean production. Understanding the physiological responses of soybean plants to herbicide application timing and types allows for the development of evidence-based weed management strategies that maximize productivity while minimizing environmental impact and production costs (Kadam et al., 2018). Further research is needed to explore the long-term effects and sustainability of integrated weed management practices in diverse agroecosystems to ensuring the continued success of soybean cultivation in the face of evolving weed pressures and environmental challenges.

CONCLUSIONS

The results thoroughly evaluate the effect of pre and post emergence herbicides and hand hoeing practices on soybean cultivation. The findings significantly support the postulated hypothesis regarding the pre and post emergence herbicides on soybean growth, yield and quality. Based on the research findings, it is recommended that the use of sequential application of herbicide treatments, specifically s-metolachlor + pendimethalin as PRE with fluazifop-p-butyl as POST herbicide showed the higher number of plant population, plant height, pod development, seed counts, 100-grain weights and days to flowering resulting in higher seed and stover yields also led to higher protein content, oil content and oil yield in soybean. These findings showed the importance of sequential application of herbicides for timely weed control in soybean. While, the sole post emergence herbicide fluazifop-p-butyl or haloxyfop-p-ethyl showed lower values for various growth parameters in both 2022 and 2023. Therefore, it is important the sequential application of s-metolachlor + pendimethalin as PRE with fluazifop-p-butyl as POST herbicide to ensure the highest possible grain yield, protein content and oil yield. Additionally, the sequential application of s-metolachlor + pendimethalin as PRE with fluazifop-p-butyl as POST herbicide showed higher weed control efficiency (88.89%), weed control percentage (44.59% to 75.65%), herbicide efficiency index (10.11%) and weed index showed lowest yield (11.43% and 7.19%) losses due to weeds while the highest yield (27.16%) losses was observed in sole Post-application of haloxyfop-p-ethyl herbicide. So, it is recommended the sequential application of herbicide treatments, s-metolachlor + pendimethalin as a pre-emergence followed by fluazifop-p-butyl as a post-emergence herbicide, to optimize soybean growth parameters, yield attributes, and quality parameters. These findings showed significance of timely weed control in soybean cultivation. However, it is also advisable to integrate manual hoeing practices, particularly in situations where weed pressure is high or as part of a diversified weed management strategy. By adopting these recommendations, farmers can make informed decisions to enhance soybean cultivation practices, ensuring sustainable productivity and profitability while minimizing weed-related losses. This study contributes valuable insights to the agricultural community, facilitating the development of effective weed management strategies for soybean production and advancing global food security efforts.

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