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RESEARCH ARTICLE

Comparative performance of Haloxyfop-R-methyl formulations on weed suppression, growth and energy use in soybean (*Glycine max* L.) cultivation

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Abstract

Soybean cultivation during the rainy (*Kharif*) season frequently encounters severe weed infestations, which compete with the crop for essential resources and result in substantial yield losses if not effectively managed. To address this challenge, a field experiment was conducted during the 2022-2023 rainy season at the Agricultural Research Farm of Banaras Hindu University, Varanasi, Uttar Pradesh, India. The study employed a randomized block design with three replications and eight treatments, comprising different doses and sources of haloxyfop-R-methyl 10.5 % EC, propaquizafop 10 % EC, a weed-free plot and an untreated control. Among the herbicidal treatments, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at a concentration of 0.33 g/L (T_3) demonstrated the most effective weed suppression, which translated into improved crop growth and higher yield performance. This treatment significantly reduced weed density and biomass accumulation, thereby enhancing weed control efficiency, weed control index, treatment efficiency index and crop resistance index, while simultaneously lowering the weed persistence index. As a result, T_3 recorded a higher stover yield of 2152 kg/ha and a seed yield of 1499 kg/ha, along with an improved harvest index of 41.22 %. Additionally, substantial increases were observed in energy use efficiency (49.14 %), energy efficiency ratio (50.63 %), energy productivity (50.81 %) and energy profitability (53.83 %) in comparison to the untreated control. Thus, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L represents a viable, efficient and sustainable weed management strategy for maximizing soybean productivity and profitability under rainy season conditions in the eastern Indo-Gangetic plains of India.

Keywords: haloxyfop-R-methyl; summed dominance ratio; treatment efficiency index; weed persistence index

Introduction

Soybean (*Glycine max* (L.) Merrill) is a vital oilseed crop cultivated globally due to its adaptability, high nutritional value and diverse uses across food, feed and industrial applications. In India, soybean is grown on approximately 12.1 million hectares with a production of 11.2 million metric tons, yet its average productivity remains low at 921 kg/ha, far below the potential of 2500 kg/ha (1). Several constraints contribute to this yield gap, with weed competition standing out as one of the most significant challenges for soybean farmers. Soybean, a *Kharif* season crop characterized by wide inter-row spacing and slow initial growth, is particularly vulnerable to weed interference during the critical period of crop-weed competition, typically between 30 and 45 days after sowing. During this period, unchecked weed competition can cause yield losses ranging from 20 % to 48 % and under severe conditions, potential losses may reach 50 % to 76 % (2). Therefore, effective weed management is essential for improving soybean productivity. One of the most adopted methods for weed control in soybean is manual hand weeding. Although this approach is effective, it has become increasingly impractical due to its labour-intensive and time-consuming nature, especially during peak periods of agricultural operations. As a result, chemical weed control has emerged as a more widely adopted and cost-effective alternative, offering greater ease and operational efficiency for farmers. Common chemical weed management practices in soybean cultivation involve the use of both pre-emergence and post-emergence herbicides, with imazethapyr and pendimethalin being among the most widely applied (3). Imazethapyr has demonstrated effectiveness as a post-emergence herbicide, particularly in controlling a broad spectrum of grassy weed species (4). However, its effectiveness has declined over time due to the development of herbicide resistance (5). Imazethapyr belongs to the ALS (acetolactate synthase) inhibitor group, a class increasingly linked to weed resistance issues, highlighting the need for new herbicides with different mechanisms of action. Further, relying solely on pre-emergence (PRE) herbicides like pendimethalin may not be a feasible option for season-long management, as late-emerging weeds will compete with soybeans and reduce yields. Along with this, unfavourable weather may prevent pendimethalin application, necessitating alternative post-emergence (POST) herbicides (6). In this context, haloxyfop-R-methyl can be an effective herbicide for soybean weed management. It works by inhibiting the enzyme acetyl-CoA carboxylase (ACCase), which plays a critical role in synthesizing fatty acids necessary for plant cell membrane formation. Haloxyfop-R-methyl offers potential efficacy against weeds that have developed resistance to traditional ALS inhibitors. However, limited research has been conducted to evaluate its efficacy across different crops and agro-ecological conditions (7, 8). Additionally, in the eastern Indo-Gangetic Plains of India, no comprehensive studies have been conducted to evaluate the efficacy of different formulations of haloxyfop-R-methyl in soybean cultivation. The present study addresses this research gap, hypothesizing that the application of haloxyfop-R-methyl at optimized formulation and dosages can improve weed control and enhance soybean productivity. The objective is to evaluate various doses and application timings of haloxyfop-R-methyl to identify the most effective strategy for managing weed pressure in soybean fields, thereby contributing to sustainable and effective weed management solutions.

Material and Methods

The experiment was conducted during the rainy (*Kharif*) season of 2022-23 at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh (25°18′ N latitude and 83°03′ E longitude, at 75.7 meters above sea level). The soil in the experimental field is Entisol, characterized by deep, flat, well-drained conditions, moderate fertility, a bulk density of 1.4 Mg/m^3, a near-neutral pH of 7.3, low organic carbon (0.3 %), low available nitrogen (210.3 kg/ha), medium available phosphorus (18.1 kg/ha) and medium available potassium (176.9 kg/ha). The soybean variety used in the experiment was JS 20-98, with row spacing of 45 cm and 10 cm between plants. A basal dose of 23.5, 60, 20 NPK kg/ha and 20 kg/ha sulphur was applied before sowing. During the cropping period, there was 1200.4 mm of intermittent rainfall. During the growing season, the average weekly temperature was 30.5 °C. The experiment followed a randomized block design with three replications and eight treatments *viz.,* T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot and T_8 - untreated Control (weedy check). Gallant (market sample) is a herbicide that contains haloxyfop-R-methyl as its active ingredient, which is a product of Dow AgroSciences, while the BCSPL sample is a new formulation of haloxyfop-R-methyl made by Best Crop Science Private Limited (BCSPL), used in this study. To evaluate their effectiveness under similar conditions, all herbicides were applied post-emergence at 20 days after sowing (DAS) using a knapsack sprayer equipped with a flat-fan nozzle. The respective doses of each herbicide were dissolved in 500 L of water and uniformly applied over one hectare of land to ensure consistent coverage across treatments. Weed density and biomass for each species were assessed at 50, 65 and 80 DAS. Samples were taken from two locations within each plot using a 0.5 m^2 quadrat and the data were converted to a per-square-meter basis. In each quadrat, weeds were counted, cut near the soil surface and collected for sun-drying, followed by oven drying at 70 °C for five days. The dried samples were weighed separately to determine dry matter accumulation. Before statistical analysis, weed density and dry weight data were transformed using a square root transformation and the results were presented in tabular form.

Summed Dominance Ratio (SDR), a measure of dominance of a weed species, was computed using the following equation (9).

$$\text{SDR (\%)} = [\text{Relative Density (RD)} + \text{Relative Biomass (RB)}] / 2 \qquad \text{(Eqn. 1)}$$

where, $\text{RD} = (\text{density of a weed species/total density}) \times 100$; (Eqn. 2)

$\text{RB} = (\text{biomass of a weed species/total biomass}) \times 100$ (Eqn. 3)

Weed Control Efficiency (WCE) based on weed density and Weed Control Index (WCI) based on weed biomass were calculated to judge to efficacy of treatments (10, 11).

$$\text{WCE (\%)} = [(W_{PC} - W_{PT}) / W_{PC}] \times 100 \qquad \text{(Eqn. 4)}$$

$$\text{WCI (\%)} = [(W_C - W_T) / W_C] \times 100 \qquad \text{(Eqn. 5)}$$

Several weed indices, viz. Treatment Efficiency Index (TEI), Crop Resistance Index (CRI) and Weed Persistence Index (WPI) were calculated using the following equations (12).

Treatment Efficiency Index (TEI):

$$\text{TEI (\%)} = \frac{Y_T - Y_C/Y_C}{W_T/W_C} \qquad \text{(Eqn. 6)}$$

Crop resistance index (CRI):

$$\text{CRI} = \frac{CDW_T \times W_C}{CDW_C \times W_T} \qquad \text{(Eqn. 7)}$$

Weed persistence index (WPI):

$$\text{WPI (\%)} = \frac{W_T \times W_{PC}}{W_C \times W_{PT}} \times 100 \qquad \text{(Eqn. 8)}$$

Where, W_T = Weed dry weight of treated plot, W_C = Weed dry weight of control (unweeded) plot, W_{PT} = Weed population in treated plot, W_{PC} = Weed population in control (unweeded) plot, Y_T= Yield of treated plot, Y_C= Yield of control (unweeded) plot, CDW_T = Crop dry weight in treated plot, CDW_C = Crop dry weight in control (un-weeded) plot.

The energy indices for soybean production were calculated using all inputs utilized during cultivation and the outputs obtained, including grain and straw. The energy input for each component across all treatments was determined by multiplying the quantity of the input (Qi) by its corresponding energy coefficient (Table 1).

$$\text{Input energy (MJ /ha)} = \Sigma\ [Q_i \times (\text{energy coefficient})_i] \quad \text{(Eqn. 9)}$$

$$\text{Output energy (MJ/ha)} = [\text{grain yield (kg/ha)} \times \text{energy coefficient of grain (MJ/kg)}] + [\text{straw yield (kg/ ha)} \times \text{energy coefficient of straw (MJ/kg)}] \quad \text{(Eqn. 10)}$$

The energy use indices, including Net Energy (NE), Energy Use Efficiency (EUE), Energy Efficiency Ratio (EER), Energy Productivity (EP_d), Energy Profitability (EP_f) and Specific Energy (SE) were calculated using the equations given below (13-16).

$$\text{NE (MJ/ha)} = \text{Total output energy (MJ/ha) - Total input energy (MJ/ha)} \quad \text{(Eqn. 11)}$$

$$\text{EUE} = \text{Total output energy (MJ/ha) / Total input energy (MJ/ha)} \quad \text{(Eqn. 12)}$$

$$\text{EER} = \text{Total grain output energy (MJ/ha) / Total input energy (MJ/ha)} \quad \text{(Eqn. 13)}$$

$$P_d \text{ (kg/MJ)} = \text{Grain yield (kg/MJ) / Total input energy (MJ/ha)} \quad \text{(Eqn. 14)}$$

$$EP_f = \text{Net energy return (MJ/ha) / Total input energy (MJ/ha)} \quad \text{(Eqn. 15)}$$

$$\text{SE (MJ/kg)} = \text{Total input energy (MJ/ha) / Grain yield (kg/ha)} \quad \text{(Eqn. 16)}$$

The data analysis was conducted using a randomized complete block design, with statistical tests performed through analysis of variance (ANOVA) (20). Standard Error of Means (SEm±) and Fisher's Least Significant Difference (LSD) at the 5 % significance level were calculated for each treatment using RStudio version 2023.03.0-daily+82.pro2.

Results and Discussion

Status of weed flora

The weedy check plots exhibited a variety of weed species throughout the growth period. The dominant species observed in the experimental field included *Cynodon dactylon* (L.) Pers., identified as perennial grasses; *Phyllanthus niruri* (L.), *Lindernia procumbens* (L.), *Parthenium hysterophorus* (L.), *Eclipta alba* (L.) all identified as broad-leaved weeds; and *Cyperus esculentus* (L.) recognized as perennial sedges.

Relative distribution and dominance of weeds in the unweeded control plot

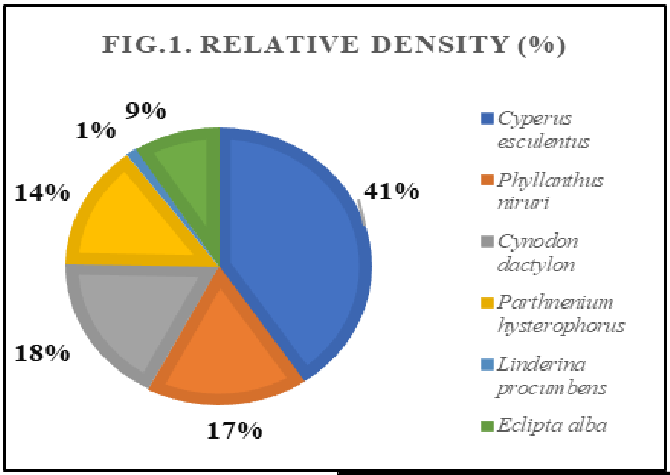
The relative distribution of various weed species was assessed at 20 DAS. *Cyperus esculentus* (L.) exhibited the highest relative density (40.58 ± 0.55 %) and relative dry weight (48.14 ± 0.34 %), indicating its strong competitive presence in the field. In contrast, *Lindernia procumbens* exhibited the lowest relative density (1.25 ± 0.01 %) and relative dry weight (3.17 ± 0.07 %). Consequently, *Cyperus esculentus* (L.) also registered the highest Summed Dominance Ratio (SDR) at 44.36 ± 0.84 %, while *Lindernia procumbens* had the lowest SDR (2.21 ± 0.04 %). These findings clearly identify *Cyperus esculentus* (L.) as the most dominant weed species in the experimental plots. Additionally, *Phyllanthus niruri* (L.) emerged as the most prevalent dicot weed (Fig. 1, 2 & 3). Similar weed species associated with soybean cultivation have also been reported in earlier studies further supporting these observations (21).

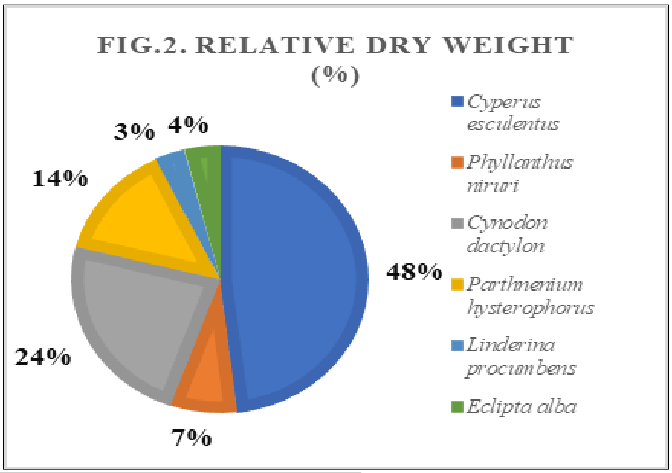
Total weed density and dry weight of weeds across treatments at different intervals

The data regarding total weed density and total dry weight was taken at 50, 65 and 80 DAS. The weedy check plots exhibited the highest weed density and dry weight on all observation dates, owing to the unchecked growth of weeds in the absence of any weed management practices. The weed -free plot recorded the lowest weed density and dry weight among all treatments, which can be attributed to effective

Table 1. Energy coefficients of various input and outputs

Particulars	Unit	Energy coefficients (MJ /unit)	References
a. *Input* 1. Human labour adult man	hr	1.96	(14, 15)
adult woman	hr	1.57	(14, 15)
2. tractor	kg	64.8	(14, 15)
3. farm machinery Disc harrow, cultivator/ seed drill/ sprayer	kg	62.7	(14, 15)
Combine harvester	kg	83.5	(14, 15)
4. Diesel including lubricant	litre	56.31	(17)
5. electricity	kWh	11.93	(17)
6. Water	m^3	1.02	(13)
7. fertilizer a) N	kg	60.6	(14, 15)
b) K_2O	kg	6.7	(16)
c) S	kg	1.5	(18)
8. superior chemical granular	kg	120	(16)
liquid	mL	0.102	(16)
9. seed soybean	kg	34	(14)
B. *Output* 1. Soybean grain	kg	34	(19)
2. Soybean straw	kg	19.4	(19)





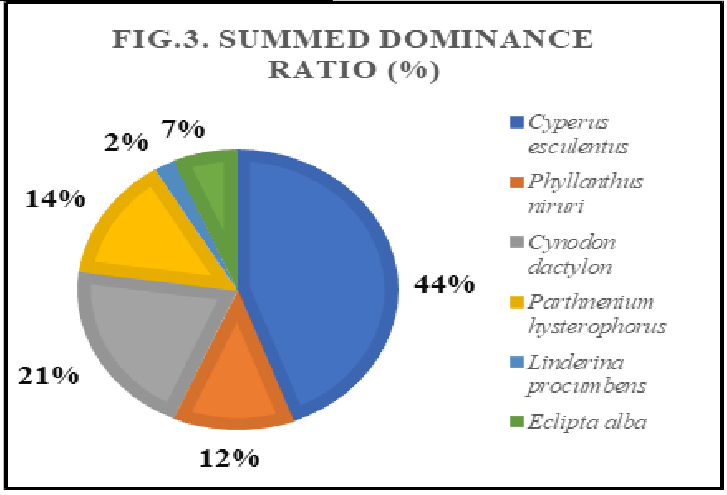


Fig. 1, Fig. 2 and **Fig. 3.** Relative density, dry weight and summed dominance ratio of weeds in the unweeded control plot, respectively.

weed control during the critical period of crop-weed competition and the complete elimination of weeds. Haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3) recorded the lowest total weed density and dry weight among all herbicide treatments (Table 2). The inclusion of haloxyfop-R-methyl at varying dosages and from different sources (BCSPL and market samples), alongside propaquizafop and manual weed management, was intentional and strategic. This approach enabled a comparative evaluation of efficacy across chemical formulations and concentrations, considering the increasing prevalence of herbicide-resistant grassy weeds and the practical limitations of manual weeding. Although both formulations contained the same active ingredient, haloxyfop-R-methyl, the superior performance of the BCSPL sample, particularly at 0.33 g/L, may be attributed to differences in formulation chemistry, including adjuvant quality, emulsification behaviour, higher dose and possibly enhanced absorption or persistence characteristics. It was observed that effective weed control, whether achieved through chemical herbicides or manual weeding, led to a significant reduction in both weed density and dry weight (22).

Effect of different treatments on density and dry weight of weed species at 50 DAS

Cyperus esculentus (L.) emerged as the most dominant weed species, with the weedy check exhibiting the highest density and dry weight of all weed species during observations at 50 DAS (Table 3). Among the herbicidal treatments, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3),

Table 2. Weed density and biomass at 50, 65 and 80 DAS in Soybean under different treatments

Treatments	**Total weed density (number/ m²)**			**Total weed biomass (g /m²)**		
	50 DAS	**65 DAS**	**80 DAS**	**50 DAS**	**65 DAS**	**80 DAS**
T_1	65.96^{cd}	68.18^{c}	53.95^{c}	31.57^{d}	70.20^{c}	27.34^{cd}
T_2	61.55^{e}	64.15^{d}	48.47^{e}	28.70^{e}	64.83^{d}	24.82^{e}
T_3	58.23^{f}	57.43^{e}	43.21^{f}	25.90^{f}	58.18^{e}	22.40^{f}
T_4	63.38^{de}	66.35^{cd}	51.20^{d}	30.10^{de}	67.46^{cd}	26.42^{d}
T_5	71.71^{b}	73.98^{b}	58.87^{b}	35.81^{b}	75.41^{b}	30.22^{b}
T_6	69.16^{bc}	71.88^{b}	57.43^{b}	33.41^{c}	73.89^{b}	28.83^{bc}
T_7	36.49^{g}	43.64^{f}	31.90^{g}	13.63^{g}	43.75^{f}	17.06^{g}
T_8	92.89^{a}	101.49^{a}	88.70^{a}	62.21^{a}	96.71^{a}	45.65^{a}
LSD (p=0.05)	3.21	2.61	2.65	1.55	3.18	1.57

[v]Square-root [(x + 0.5)1/2] transformed values of the observed weed density and biomass; Means with at least one letter common are not statistically significant using fisher's LSD at $\alpha = 0.05$; **indicates significance at $p < 0.01$, T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot and T_8 - untreated control (weedy check)

Table 3. Weed density and biomass at 50 DAS of different weed species in soybean under different treatments

Treatments	Weed species density (number/m²)						Weed species dry biomass (g /m²)					
	Cyperus esculentus	*Phyllanthus niruri*	*Cynodon dactylon*	*Parthnenium hysterophorus*	*Linderina procumbens*	*Eclipta alba*	*Cyperus esculentus*	*Phyllanthus niruri*	*Cynodon dactylon*	*Parthnenium hysterophorus*	*Linderina procumbens*	*Eclipta alba*
T_1	25.33^d	7.87^b	3.90^d	10.03^{bc}	10.25^c	8.58^c	14.29^{cd}	2.96^d	3.13^c	5.33^d	3.32^c	2.54^c
T_2	24.58^d	6.88^d	3.33^{ef}	9.27^d	9.48^d	8.01^d	13.72^{de}	2.66^e	2.84^d	4.39^f	3.01^d	2.09^e
T_3	23.50^e	6.10^e	3.20^f	8.64^e	8.80^e	7.99^d	13.19^e	2.25^f	2.56^e	3.73^g	2.66^e	1.53^g
T_4	24.98^d	7.30^c	3.52^e	9.81^c	9.66^{cd}	8.11^d	14.09^{cd}	2.72^e	2.92^d	4.91^e	3.23^{cd}	2.23^d
T_5	28.36^b	8.20^b	4.61^b	10.33^b	10.99^b	9.23^b	15.36^b	3.67^b	3.93^b	6.18^b	3.75^b	2.92^b
T_6	27.23^c	7.97^b	4.11^c	10.15^{bc}	10.87^b	8.84^{bc}	14.62^c	3.36^c	3.30^c	5.88^c	3.44^c	2.80^b
T_7	18.60^f	3.27^f	2.09^g	4.48^f	5.59^f	2.46^e	6.36^f	1.83^g	1.02^f	1.50^h	1.20^f	1.71^f
T_8	34.07^a	10.54^a	7.40^a	13.20^a	14.59^a	13.09^a	20.53^a	9.21^a	6.64^a	8.63^a	10.78^a	6.43^a
LSD (p=0.05)	1.07	0.35	0.20	0.49	0.59	0.44	0.61	0.16	0.21	0.25	0.29	0.14

^{w}Square-root [(x + 0.5)1/2] transformed values of the observed weed density and biomass; Means with at least one letter common are not statistically significant using fisher's LSD at $\alpha = 0.05$; **indicates significance at $p < 0.01$, T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot and T_8 - untreated control (weedy check)

followed by haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.26 g/L (T_2), resulted in the lowest weed density and dry weight of all weed flora. Additionally, hand weeding at 20 and 40 DAS demonstrated the lowest density and dry weight of all weed species across all treatments. The post-emergence application of herbicide reduced weed biomass by 61.44 %; however, hand weeding proved to be more effective, achieving a reduction of 98.6 % (23).

Weed Control Efficiency (WCE) and Weed Control Index (WCI) of different treatments

Hand weeding at 20 and 40 days after sowing (DAS) resulted in the highest weed control efficiency (60.72 %) and weed control index (78.09 %) among all treatments (Fig. 4). This result can be attributed to the thorough and timely weed management during the critical period of crop-weed competition, which led to significantly reduced weed density and dry matter accumulation at 50 DAS. Among the herbicide treatments, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3), followed by haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.26 g/L (T_2), demonstrated significantly higher WCE and WCI. The haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L (T_3) exhibited superior control over all weed species for an extended period, resulting in lower weed density and dry weight, making it a more effective chemical option compared to other herbicide treatments. Earlier research demonstrated the effectiveness of haloxyfop-R-methyl in controlling weed populations and emphasized the significance of timely and effective weed management strategies (24).

Treatment Efficiency Index (TEI), Crop Resistance Index (CRI) and Weed Persistence Index (WPI) of different treatments

The data related to various weed indices were statistically analysed (Table 4). The TEI was highest in the weed-free plot (1.53), primarily due to effective weed control that resulted in reduced dry matter accumulation, fostering an optimal environment for crop growth and development. Among the chemical treatments, application of haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L (T_3) followed by haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.26 g/L (T_2) achieved the higher TEI. Conversely, haloxyfop -R-methyl 10.5 % w/w EC (market sample) at 0.26 g/L (T_5) demonstrated the lowest TEI. These results indicate that formulation quality and application rate are critical in determining herbicide efficacy. A higher treatment efficiency index indicates greater efficacy of specific treatments in controlling weeds. The CRI gauges a crop's capacity to withstand weed stress, indicating its resilience and adaptability. Hand weeding at 20 and 40 DAS recorded the highest CRI (9.51), creating an ideal environment for crop dry matter production while suppressing weed growth. Among chemical treatments, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L (T_3) achieved the highest CRI (5.79), whereas haloxyfop-R-methyl 10.5 % w/w EC (market sample) at 0.26 g/L (T_5) had the lowest CRI (3.10). The WPI was highest for haloxyfop-R-methyl 10.5 % w/w EC (market sample) at 0.26 g/L (T_5) and lowest for the BCPSL sample at 0.33 g/L (T_3) among chemical treatments, with the weed-free plot

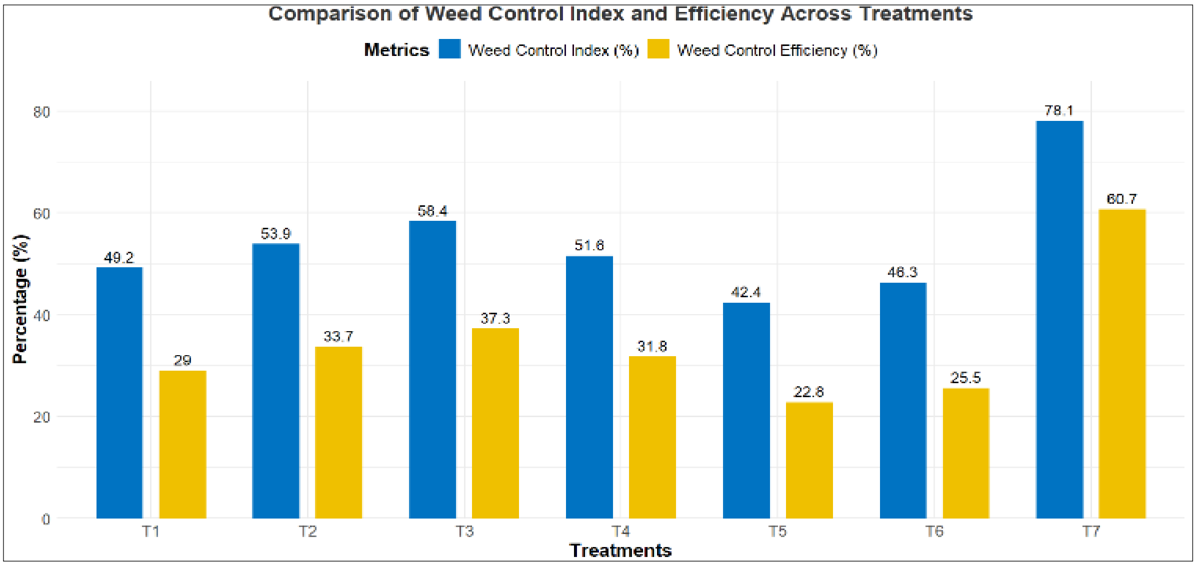


Fig. 4. Effect of different treatments on WCE and WCI at 50 DAS in soybean.

Table 4. Effect of herbicidal treatments on different weed indices in soybean

Treatments	Treatment efficiency index	Crop resistance index	Weed persistence index
T_1	0.51^{e}	3.58^{d}	0.71^{b}
T_2	0.71^{c}	4.59^{c}	0.70^{b}
T_3	0.86^{b}	5.79^{b}	0.66^{c}
T_4	0.62^{d}	3.37^{e}	0.71^{b}
T_5	0.39^{g}	3.10^{f}	0.75^{a}
T_6	0.46^{f}	4.43^{c}	0.72^{ab}
T_7	1.53^{a}	9.51^{a}	0.56^{d}
LSD (p=0.05)	0.03	0.21	0.03

*Means with at least one letter common are not statistically significant using fisher's LSD at α=0.05; **indicates significance at $p < 0.01$, T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot

showing the lowest WPI across all treatments. A lower WPI indicates greater weed control effectiveness. Haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L (T_3) was statistically significant and superior in controlling weed infestation over an extended period, outperforming other herbicidal treatments across all weed indices. Hoe weeding at 3 and 6 days after sowing recorded the highest weed persistence index, crop resistance index and agronomic management index, followed closely by herbicide application (25).

Growth parameters of soybean as affected by different herbicidal treatments

Hand weeding at 20 and 40 DAS resulted in the lowest plant height (52.04 cm), but it led to the highest number of branches per plant (6.60) and the highest LAI of 2.21 among all the treatments. This demonstrates the significant advantage of maintaining a weed-free environment during critical growth stages, which allows soybean plants to fully utilize available resources like sunlight, nutrients and moisture. The absence of weed competition provided a congenial environment for optimal crop growth and development. In contrast, the weedy check treatment, where no weed control was applied, experienced the lowest number of branches per plant (2.95) and the lowest LAI (1.15). The unchecked proliferation of weeds severely limits the availability of essential growth factors, which negatively affects crop vigor and development. Among the chemical treatments, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3) showed promising results, recording a higher number of branches per plant (5.34) and a relatively high LAI (2.15), which was statistically significant compared to other herbicide treatments. The superior performance of T_3 can be attributed to its prolonged weed-suppressing ability, which effectively reduced weed density and dry weight for an extended period. This allowed the soybean plants to experience less competition for resources throughout the growing season, leading to improved branching and leaf area development, both of which are crucial for higher yields (Table 5). Growth parameters of soybean improved with the application of post-emergence herbicides (26); specifically, haloxyfop applied at 0.1 and 0.125 kg/ha recorded significantly higher dry weight of plant and number of branches per plant (27).

Seed yield, stover yield and harvest index as affected by different herbicidal treatments

The results from the present study indicate that weed management practices had a significant impact on the seed yield, stover yield and harvest index of soybean (Table 5). During the growing season, the weedy check plots experienced severe weed infestation, which directly contributed to the lowest stover (1415 kg/ha) and seed yield (965 kg/ha) of soybean. This significant weed competition hindered the growth potential of crop, limiting its ability to thrive and produce effectively. In contrast, hand weeding at 20 and 40 DAS established a weed-free environment throughout the critical period of crop-weed competition. This meticulous weed management allowed for optimal

Table 5. Effect of herbicidal treatments on growth parameters and yield of soybean

Treatments	**Plant height (cm)**	**No. of branches per plant**	**Leaf area index at harvest**	**Seed yield (kg/ha)**	**Stover yield (kg/ ha)**	**Harvest index (%)**
T_1	69.94^{b}	3.57^{e}	1.96^{b}	1305^{c}	1927^{cd}	40.27^{ab}
T_2	76.89^{a}	4.53^{cd}	1.95^{b}	1437^{ab}	2034^{b}	40.92^{ab}
T_3	62.78^{c}	5.34^{b}	2.15^{a}	1499^{a}	2152^{a}	41.22^{ab}
T_4	68.60^{b}	4.71^{c}	1.82^{c}	1381^{b}	2019^{bc}	40.37^{ab}
T_5	71.10^{b}	4.45^{d}	1.59^{d}	1243^{c}	1870^{d}	40.13^{ab}
T_6	63.18^{c}	3.45^{e}	1.94^{b}	1278^{c}	1966^{bcd}	39.93^{b}
T_7	52.04^{d}	6.60^{a}	2.21^{a}	1453^{a}	1944^{bcd}	41.57^{a}
T_8	63.73^{c}	2.95^{f}	1.15^{e}	965^{d}	1415^{e}	40.23^{ab}
LSD (p=0.05)	2.60	0.19	0.07	63.84	106.09	1.59

^{y}Means with at least one letter common are not statistically significant using fisher's LSD at α = 0.05; **indicates significance at $p < 0.01$, T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot and T_8 - untreated control (weedy check)

conditions for soybean growth and development, resulting in markedly higher yields and the highest harvest index (41.57 %) among all treatments. Among the various chemical treatments applied, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at a rate of 0.33 g/L (T_3) demonstrated a superior performance, achieving significantly higher stover (2152 kg/ha), seed yield (1499 kg/ha) and harvest index (41.22 %). Conversely, the weedy check plot had the lowest harvest index, attributed to the excessive weed competition throughout the crop's growth period, which negatively impacted both seed and stover yields. Interestingly, the weedy check recorded a higher harvest index than the propaquizafop 10 % EC applied at 0.15 g/L (T_6), likely due to the relatively lower seed yield in T_6 in proportion to its stover yield. Kumar et al. reported that unweeded check recorded the highest harvest index (27.1 %) among all the treatments, but the results are non-significant (26). This impressive outcome can be attributed to the haloxyfop-R-methyl efficacy in effectively suppressing weed growth, thereby creating a more favourable environment for soybean growth. By minimizing weed competition, haloxyfop-R-methyl allowed the soybean plants to access essential resources, leading to enhanced crop development and productivity. The haloxyfop applied at the rate of 0.1 kg/ha recorded the highest seed yield, whereas unweeded check resulted lowest seed yield (27).

Energetics estimation under different treatment

Among the treatments evaluated (T_1-T_8), haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3) demonstrated superior performance in multiple energy indices compared to the untreated control (weedy check). This treatment significantly increased EUE, EER, EP_d and EP_f by 49.14 %, 50.63 %, 50.81 % and 53.83 %, respectively, over the untreated control (Table 6). A slightly lower application rate of 0.26 g/L (T_2) of the same product followed closely in terms of these metrics. Haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L (T_3) required substantially less specific energy (SE), defined as the energy needed to produce a unit of yield, exhibiting a 33.6 % reduction in SE compared to the untreated control. These improvements in energy indices were strongly correlated with higher crop yields, which in turn were linked to improved WCE and WCI across treatments (Fig. 4). The treatment haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) with 0.33 g/L (T_3) application rate achieved the highest energy output and net energy returns due to its superior yield performance. Similarly, this trend was observed in other energy-related indices (EUE, EER, EP_d and EP_f), reinforcing its overall effectiveness. These results indicate that the higher yield achieved with this treatment not only maximized energy output but also enhanced energy returns relative to energy input. The superior performance of this treatment highlights its capability to generate higher output, both in energy and economic terms, per unit of energy consumed. Additionally, its reduced specific energy requirement per unit of grain yield further underscores its efficiency, making it a highly advantageous choice for optimizing energy use in soybean production. This approach demonstrates a significant potential for achieving sustainable and profitable weed management practice through efficient energy utilization.

Table 6. Energy indices under different herbicidal treatments

Treatments	**Energy ($\times 10^3$ MJ /ha)**		**Energy use efficiency**	**Energy efficiency ratio**	**Energy productivity (Kg/MJ)**	**Energy profitability**	**Specific energy (MJ/Kg)**
	Output energy	**Net energy**					
T_1	81.75^{c}	76.44^{cd}	15.39^{c}	8.35^{c}	0.246^{c}	14.390^{c}	4.071^{c}
T_2	88.32^{b}	82.98^{ab}	16.55^{b}	9.15^{ab}	0.269^{ab}	15.547^{b}	3.714^{de}
T_3	92.71^{a}	87.35^{a}	17.27^{a}	9.49^{a}	0.279^{a}	16.267^{a}	3.582^{e}
T_4	86.12^{b}	80.81^{bc}	16.21^{b}	8.84^{b}	0.260^{b}	15.213^{b}	3.847^{d}
T_5	78.54^{c}	73.20^{d}	14.71^{d}	7.92^{d}	0.233^{d}	13.715^{d}	4.294^{b}
T_6	81.59^{c}	76.31^{cd}	15.43^{c}	8.22^{cd}	0.242^{cd}	14.434^{c}	4.137^{c}
T_7	87.12^{b}	81.83^{b}	16.49^{b}	9.35^{a}	0.275^{a}	15.485^{b}	3.637^{e}
T_8	60.26^{d}	55.05^{e}	11.58^{e}	6.30^{e}	0.185^{e}	10.575^{e}	5.395^{a}
Significance	**	**	**	**	**	**	**

^{z}Means with at least one letter common are not statistically significant using fisher's LSD at α = 0.05; **indicates significance at $p < 0.01$, T_1 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.21 g/L; T_2 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.26 g/L; T_3 - haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) 0.33 g/L; T_4 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.21 g/L; T_5 - haloxyfop-R-methyl 10.5 % w/w EC (market sample) 0.26 g/L; T_6 - propaquizafop 10 % EC 0.15 g/L, T_7 - weed free plot and T_8 - untreated control (weedy check)

Conclusion

Effective weed management is essential for optimizing soybean growth, productivity and energy efficiency. Among the treatments evaluated, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) applied at 0.33 g/L (T_3) as a post-emergence application at 20 DAS emerged as the most effective strategy. This formulation resulted in the lowest total weed density, weed dry weight and weed persistence index, while achieving the highest treatment efficiency index and crop resistance index among all herbicidal treatments. As a result of effective weed suppression, T_3 also recorded a higher seed yield (1499 kg/ha), stover yield (2152 kg/ha) and harvest index (41.22 %). In addition to superior agronomic performance, significant improvements in energy-related indices were observed. Energy use efficiency and energy profitability increased by over 50 % compared to the weedy check and the specific energy requirement was markedly reduced, which highlights its potential to support resource-efficient and sustainable crop production. Thus, haloxyfop-R-methyl 10.5 % w/w EC (BCSPL sample) at 0.33 g/L offers a practical, efficient and sustainable solution for optimizing soybean productivity and profitability.

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Authors' contributions

AS_1 carried out the investigation, formulating the methodology and writing of the original manuscript. JKS participated in drafting of objectives and writing of draft. SKR participated in writing and editing of draft. KP participated in designing and writing of manuscript. KSR participated in statistical analysis and writing of draft. AS_2 participated in writing and editing of draft. AS_3 and MS participated in final editing of draft. All authors read and approved the final manuscript.

Compliance with ethical standards

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