



WEED MANAGEMENT IN CHIA (*Salvia hispanica* L.) THROUGH HERBICIDE APPLICATIONS UNDER SEMI-ARID CONDITIONS OF INDIA

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(Received 12 April, 2025; accepted 21 August, 2025)

ABSTRACT

A field experiment was conducted under arid conditions of western Rajasthan (India) to evaluate the efficacy of pre- and post-emergence herbicides for weed management in chia (*Salvia hispanica* L.). The study employed a randomized block design with ten treatments, comprising of two doses each of bentazon (500 and 750 g ha⁻¹), fluazifop-p-butyl (100 and 200 g ha⁻¹), sulfentrazone (50 and 75 g ha⁻¹), and pendimethalin (200 and 400 g ha⁻¹), and weed-free control, and a weedy check. Key weed control indices viz., weed control index (WCI), weed persistence index (WPI), crop resistance index (CRI), and herbicide efficiency index (HEI), were assessed along with crop growth and yield parameters. The results revealed that sulfentrazone @ 75 g ha⁻¹ and pendimethalin @ 400 g ha⁻¹, applied as pre-emergence herbicides, provided superior early-season weed control with WCI values of 85.4 and 82.7% at 30 days after sowing (DAS), respectively. Among post-emergence treatments, bentazon @ 750 g ha⁻¹ gave highest WCI (83.2%) at harvest and demonstrated superior CRI (9.33) and HEI (2.45), indicating strong crop safety and herbicide effectiveness. The highest seed yield (554 kg ha⁻¹) was obtained in weed-free treatment, followed by bentazon @ 750 g ha⁻¹ (495 kg ha⁻¹) and sulfentrazone @ 75 g ha⁻¹ (467 kg ha⁻¹) treatments, showing the respective yield increases of 90.4 and 60.5% over weedy check. The study suggested that an integrated weed management approach, combining pre-emergence herbicides (sulfentrazone or pendimethalin) with post-emergence bentazon, can significantly improve weed control and productivity in chia under arid farming systems.

Keywords: Arid agriculture, bentazon, chia, crop resistance index, herbicide efficacy, sulfentrazone, weed control index

INTRODUCTION

Chia (*Salvia hispanica* L.), a member of the Lamiaceae family, is a medicinal and dietary plant native to Mexico and Guatemala (Ixtaina *et al.*, 2008). The seeds are recognized for their exceptional nutritional profile, comprising 16-26% protein, 31-34% fat, 37-45% carbohydrates, and 23-35% total dietary fiber (Marcinek and Krejpcio, 2017). Further, chia seeds are rich in essential minerals (like calcium, phosphorus, potassium, and magnesium), vitamins (thiamine, riboflavin, niacin, folic acid, ascorbic acid, and vitamin A), and antioxidant compounds (Mohd *et al.*, 2012). Notably, chia seeds

are a powerhouse of omega-3 fatty acids and bioactive polyphenolic compounds, contributing to their health-promoting properties (Punia and Dhull, 2019). The growing interest in chia is driven by its potential to address critical global challenges, including malnutrition, climate change, and soil degradation. As a high-value pseudocereal, chia exhibits promising agronomic traits such as climate resilience and economic viability, making it a candidate for sustainable food systems. However, despite its increasing popularity, the cultivation practices and agronomic management of chia remain insufficiently developed relative to staple crops, necessitating further scientific investigation.

Effective weed management is vital to realize the full agronomic potential of chia. The crop's slow initial growth and delicate seedling stage render it highly susceptible to weed competition, which can severely impede resource acquisition - light, nutrients and water - resulting in substantial yield reductions ranging from 30 to 70%, depending on weed species and infestation intensity. Manual weed control is often impractical due to the crop's fragility and labour requirements, while mechanical weeding risks damaging plants. Consequently, selective chemical weed control using herbicides is emerging as a practical and efficient alternative. Moreover, weed infestation during critical growth stages can compromise seed quality by contaminating the harvest with weed seeds, thereby reduce market value, especially in organic and health-oriented markets. Given the relatively short crop cycle of 90-120 days, timely and efficient weed control is imperative to ensure uniform growth, maturation and optimal yield.

The cultivation of chia (*Salvia hispanica* L.) has gained considerable attention due to its nutritional and economic potential. However, effective weed management remains a critical challenge, given chia's slow initial growth and poor early competitiveness. Karkanis *et al.* (2018) evaluated the efficacy and selectivity of pre- and post-emergence herbicides under Mediterranean semi-arid conditions, demonstrating the superior early-season control achieved by pre-emergence applications of pendimethalin. Similarly, Alanbrant *et al.* (2014) highlighted the lack of registered herbicides for chia in Brazil, emphasizing the importance of selective herbicide development. Ayerza and Coates (2011) identified broadleaf weeds as predominant competitors in chia fields, indicating the need for herbicides targeting these species, such as bentazon and sulfentrazone. Falco *et al.* (2017) reinforced this by noting the limited efficacy of grass-selective herbicides in controlling broadleaf weeds in chia. Yelverton and Travis (2012) further demonstrated the potential of sulfentrazone as a selective broadleaf herbicide, supporting its use in emerging crops like chia. In India, research on chia weed management is nascent but expanding. Gupta *et al.* (2017) and Kannamreddy *et al.* (2021) advocated herbicide combinations to manage diverse weed flora in legume and pulse crops and suggested this transferable strategy to chia. Soliman and Hamza (2016) reported substantial yield losses (~ 70%) in leguminous crops due to unchecked weeds, supporting the importance of timely herbicide application. Kumar *et al.* (2024a) also observed approximately 90% yield reduction in untreated chia plots under resource-limited conditions, underscoring the critical role of weed management in semi-arid agro-ecosystems. The use of quantitative indices such as weed control index (WCI), weed persistence index (WPI), weed management index (WMI), and herbicide efficiency index (HEI) has been advocated by Mani *et al.* (1973) and Devasenapathy *et al.* (2008) to objectively assess herbicide performance. Collectively, the literature supports an integrated approach combining selective pre-emergence with post-emergence applications for weed control in chia. The present study focussed on dose optimization, and herbicide selectivity to provide a strong foundation for developing sustainable weed management strategies tailored to suit semi-arid regions. This study was aimed to evaluate the efficacy of various pre- and post-emergence herbicides in managing weed populations in chia under arid conditions. The findings were expected to contribute in developing integrated weed management strategies that may enhance crop productivity, seed quality, and economic sustainability of chia cultivation.

MATERIALS AND METHODS

A field experiment was conducted in *rabi* season 2021-2022 at the Research Farm of Agricultural

Research Station, Mandor, Agriculture University, Jodhpur, Rajasthan, India (26° 15' N to 26° 45' N latitude and 73° 00' E to 73° 29' E longitude) so as to identify suitable herbicides for weed management in chia. The experiment was laid out in a completely randomized block design with ten treatments each one replicated thrice in plots of 4.0 m × 3.0 m. The treatments comprised of different weed management practices *viz.*, bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS [days after seed sowing] (T₁), bentazon 48% SL @ 750 g ha⁻¹ @ at 30 DAS (T₂), fluazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS (T₃), fluazifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS (T₄), sulfentrazone 39.6% SC @ 50 g ha⁻¹ as pre-emergence treatment (T₅), sulfentrazone 39.6% SC @ 75 g ha⁻¹ as pre-emergence treatment (T₆), pendimethalin 38.7% CS @ 200 g ha⁻¹ as pre-emergence treatment (T₇), pendimethalin 38.7% CS @ 400 g ha⁻¹ as pre-emergence treatment (T₈), weed free control by manual weeding (T₉) and weedy check without any weed control (T₁₀). The herbicides used, their commercial names and mode of action were:

Chemical name	Commercial name	Mode of action
Sulfentrazone (39.6% SC)	Spartan	Pre-emergence/post-emergence; photosystem II inhibitor; broadleaf and some grass weed control
Pendimethalin (38.7% CS)	Dost Super	Pre-emergence; microtubule inhibitor; controls grasses and some broadleaf weeds
Bentazon (48% SL)	Basagran	Post-emergence; photosystem II inhibitor; selective for broadleaf weed control
Fluazifop-p-butyl (11.1% SL)	Fusilade	Post-emergence; ACCase inhibitor; selective grass herbicide

Chia genotype 'JCS 1' seeds, procured from the Division of Plant Breeding, ARS, Mandor, were sown on 12 October 2021 at a plant spacing of 30 cm x 10 cm with seed rate of 2.5 kg ha⁻¹ using kera method. The experimental soil was sandy loam in texture, slightly alkaline (pH, 8.2), low in organic carbon (0.13%) and available nitrogen (176 kg ha⁻¹), and medium in phosphorus respectively. (23.1 kg P₂O₅ ha⁻¹) and available potassium (330 kg K₂O ha⁻¹). The recommended doses of 40 kg N, 20 kg P, and 10 kg K ha⁻¹ were applied in the form of urea, diammonium phosphate and muriate of potash. All growth conditions were maintained as per the recommended package of practices of Agriculture University, Jodhpur (India), except for weed management. Pre-emergence herbicides were applied on the first day after seed sowing (DAS), while post-emergence herbicides were applied 30 days DAS. The weed-free treatment was maintained by manual weeding done at 20, 40, and 60 DAS.

The weed density was recorded on 30, 60, and 90 DAS and at harvest from two randomly selected spots within each plot using a quadrat of 0.25 m² area. The number of weeds within each quadrat was counted, and mean value expressed as weeds m⁻². Also, weed samples were collected from two randomly selected spots in each plot at above time intervals using the same quadrat. These were sun-dried until constant weight and then weighed to obtain dry matter. The results were expressed as g m⁻². At crop maturity, the total above-ground biomass from each net plot was harvested, dried, and weighed to assess the biological yield plot⁻¹. The data was converted to kg ha⁻¹. The produce was threshed and winnowed, and cleaned seeds were weighed at 12% moisture content to get seed yield plot⁻¹ which was converted to kg ha⁻¹. Several computations were made using following relationships:

Weed control index (WCI): Weed control index was assessed on 30, 60, 90 DAS and at harvest taking into consideration the reduction in weed population in the treated plot over the weedy check plot and expressed in percent. The WCI was assessed as follows (Mani *et al.*, 1973):

$$WCI = \frac{WP_C - WP_T}{WP_C} \times 100$$

Where WP_C = Weed population in weedy check/control plots; WP_T = Weed population in treated plot.

Weed persistence index (WPI): WPI has enough relevance in studying the aspect of weed management on comparative basis and was assessed at 30, 60, 90 DAS and at harvest as per Mishra and Misra (1997):

$$WPI = \left(\frac{\text{Weed population in control plot}}{\text{Weed population in treated plot}} \right) \times \left(\frac{\text{Weed dry weight in treated plot}}{\text{Weed dry weight in control plot}} \right)$$

Crop resistance index (CRI): CRI indicates the relationship between a proportionate increase in crop

biomass and a proportionate decrease in weed biomass in treated plot, and was assessed at 60, 90 DAS and at harvest by using the equation of Mishra and Misra (1997):

$$CRI = \left(\frac{\text{Crop dry weight in treated plot}}{\text{Crop dry weight in control plot}} \right) \times \left(\frac{\text{Weed dry weight in control plot}}{\text{Weed dry weight in treated plot}} \right)$$

Weed management index (WMI): WMI is the ratio of yield increase over control due to the weed management and percent control of weed by the respective treatment, and was computed using the following formula (Devasenapathy *et al.*, 2008):

$$WMI = \frac{\text{Per cent yield increase over control}}{\text{Per cent control of weeds}}$$

Herbicide efficiency index (HEI): HEI index represents a herbicide's potential for weed control and its phytotoxicity effect on the crop and is calculated as follows (Krishnamurthy *et al.*, 1975):

$$HEI = \left(\frac{Y_t - Y_c}{Y_c} \right) \times \left(\frac{WDM_c}{WDM_t} \right)$$

where, Y_t = crop yield from the treated plot; Y_c = crop yield from a weedy check plot; WDM_t = weed dry matter in the treated plot; WDM_c = weed dry matter in a weedy check plot

Crop growth rate (CGR): CGR was observed at 60-90 days and 90-harvest periods. CGR was calculated from the dry weight taken at various time intervals and denotes overall growth rate of crop plant. It is measured after fixed time period, irrespective of previous growth rate. The value was calculated by using the formula.

$$CGR \text{ (g/m}^2 \text{ / day)} = \frac{W_2 - W_1}{T_2 - T_1}$$

Where, $W_2 - W_1$ = Difference in oven dry biomass at the time interval; $T_2 - T_1$ = Time interval (days)

Relative growth rate (RGR): RGR was observed at 60-90 days, and 90-harvest periods. This parameter indicates rate of growth unit⁻¹ dry matter. It was computed by using formula as suggested by Dhopte and Manual (1989).

$$RGR \text{ (g / g / day)} = \frac{\text{Log}_e W_2 - \text{Log}_e W_1}{T_2 - T_1}$$

Where, W_2 and W_1 are dry matter at time T_2 and T_1 , respectively

Statistical analysis: The data was statistically analysed using 'analysis of variance' technique (Panse and Sukhatme, 1985). The critical difference (CD) for treatment comparisons was worked out where ever the variance ratio (F test) was found significant at 5% level of probability.

Harvest index (HI): HI was calculated using the formula proposed by Donald and Hamblin (1976):

$$\text{Harvest Index (HI)} = \frac{\text{Seed yield (kg ha}^{-1}\text{)}}{\text{Biological yield (kg ha}^{-1}\text{)}} \times 100$$

Statistical analysis

The data was analysed using 'analysis of variance' technique (Panse and Sukhatme, 1985). The critical difference (CD) for treatment comparisons was worked out wherever the variance ratio (F test) was significant at 5% level of probability.

RESULTS AND DISCUSSION

Weed control index (WCI)

WCI quantitatively evaluates the efficacy of weed management treatments in suppressing weed populations in relation to untreated control, with higher values indicating better weed control. In present study, the weed-free treatment consistently attained maximum WCI of 100% at all assessed growth stages (Fig. 1), thereby validating its role as a standard for complete weed suppression. Among the herbicidal treatments, pre-emergence herbicides demonstrated significantly superior weed control as compared to the post-emergence applications. Sulfentrazone @ 75 g ha⁻¹ exhibited highest WCI,

with 85.4% at 30 DAS, 69.2% at 60 DAS, and sustained effective control through to harvest (67.9%). Similarly, pendimethalin at 400 g ha⁻¹ recorded high WCI values, starting at 82.7% at 30 DAS and slightly declining to 67.8% at harvest. Treatments with lower doses of sulfentrazone and pendimethalin followed analogous trends, albeit with marginally reduced WCI values. These findings align with Karkanis *et al.* (2018) and Hasanuddin *et al.* (2022) who observed superior weed control using sulfentrazone and pendimethalin as pre-emergence herbicides in chia and legume. In contrast, post-emergence herbicides (T₁ to T₄) showed poor initial weed control, as evidenced by very low WCI values (0.3-0.6%) at 30 DAS, ascribed to delayed application. Although WCI improved later in the season, particularly with bentazon @ 750 g ha⁻¹ and fluazifop-p-butyl @ 100 g ha⁻¹, these treatments did not reach the efficacy attained by

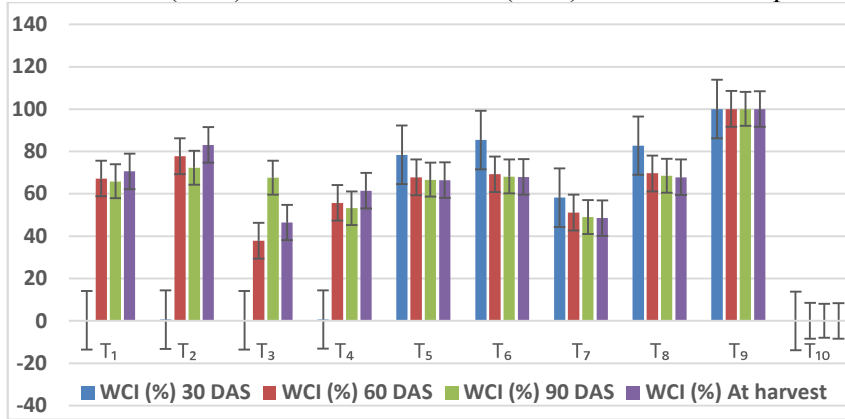


Fig. 1: Weed control index (%) as influenced by different weed management practices in chia crop; T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - Fluazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluazifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ as pre-emergence; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ as pre-emergence; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ pre-emergence; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ pre-emergence; T₉ - weed free and T₁₀ - weedy check.

pre-emergence herbicides. Similar trends were reported by Gupta *et al.* (2017) and Singh *et al.* (2019), who found limited early-season weed control with late-applied post-emergence herbicides in soybean and potato. The untreated weedy check consistently exhibited a WCI of 0%, confirming the lack of any weed suppression.

Weed persistence index (WPI)

The WPI reflects the extent of residual weed infestation under various treatments, with lower values indicating better weed suppression.

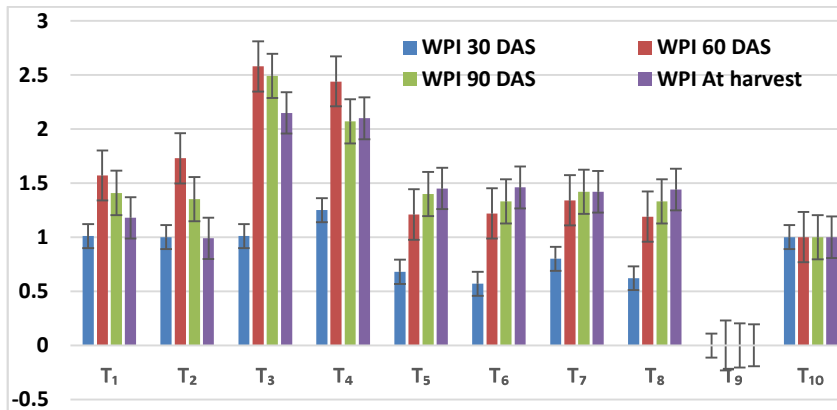


Fig. 2: Weed persistence index (WPI) as influenced by different weed management practices in chia crop; T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - Fluazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluazifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ as pre-emergence; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ as pre-emergence; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ pre-emergence; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ pre-emergence; T₉ - weed free and T₁₀ - weedy check.

Although WCI improved later in the season, particularly with bentazon @ 750 g ha⁻¹ and fluazifop-p-butyl @ 100 g ha⁻¹, these treatments did not reach the efficacy attained by pre-emergence herbicides. Similar trends were reported by Gupta *et al.* (2017) and Singh *et al.* (2019), who found limited early-season weed control with late-applied post-emergence herbicides in soybean and potato. The untreated weedy check consistently exhibited a WCI of 0%, confirming the lack of any weed suppression. Predictably, the weed-free treatment recorded the lowest WPI values (Fig. 2), reaching zero at 90 DAS, thus indicating complete weed elimination throughout the growth period. Among the herbicidal treatments, sulfentrazone @ 75 g ha⁻¹ consistently sustained the lowest WPI across all stages, ranging from 0.57 at 30 DAS to 1.46 at harvest, highlighting its superior ability to suppress weeds.

Pendimethalin @ 400 g ha⁻¹ and sulfentrazone @ 50 g ha⁻¹ also sustained low WPI values, demonstrating effective and prolonged weed control. The lower dose pendimethalin treatment showed moderate efficacy, with WPI values between 0.80 and 1.42, reflecting comparatively lesser weed suppression than the higher dose. These results concur with findings by Yelverton and Travis (2012) and Kannamreddy *et al.* (2021) who reported sustained weed suppression with sulfentrazone and pendimethalin use in legume and turfgrass systems. Post-emergence treatments generally exhibited higher WPI values, especially fluazifop-p-butyl at both 100 and 200 g ha⁻¹, which recorded WPI values as high as 2.58 at 60 DAS and 2.49 at 90 DAS, signifying poor weed control and substantial weed persistence. Gupta *et al.* (2017) similarly reported higher weed persistence in late post-emergence herbicide applications. The untreated weedy check served as the baseline with a constant WPI of 1.00.

Crop resistance index (CRI)

CRI quantitatively assesses the ability of a crop to suppress weed growth while sustaining productivity under weed competition (Fig. 3). Among the treatments, bentazon 48% SL @ 750 g ha⁻¹ significantly

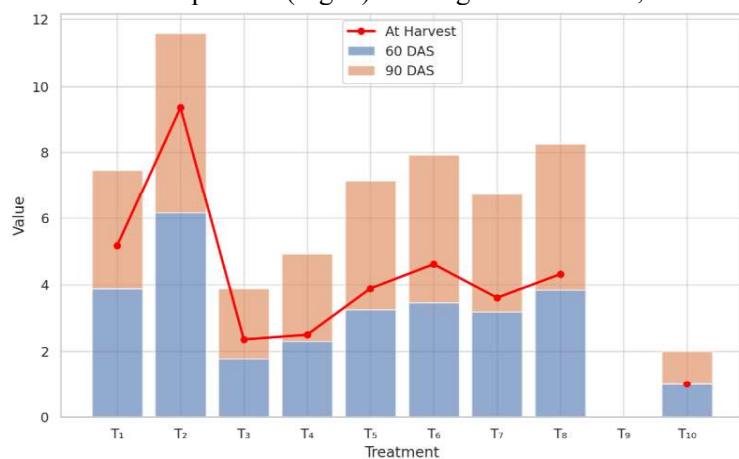


Fig. 3: Crop resistance index (CRI%) as influenced by different weed management practices in chia crop; T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - Fluazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluazifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ as pre-emergence; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ as pre-emergence; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ pre-emergence; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ pre-emergence; T₉ - weed free and T₁₀ - weedy check.

enhanced the crop's competitiveness against weeds throughout the growing season. This treatment showed highest CRI value of 6.15 at 60 DAS, which further increased to 9.33 at harvest, demonstrating its superiority over all other treatments. The progressive rise in CRI values highlights dual role of bentazon in effective weed control and in improving the crop's competitive ability over time. This is in agreement with Gupta *et al.* (2017) and Singh *et al.* (2019) who observed that bentazon application effectively enhanced crop competitiveness and suppressed weed growth in soybean and potato crops, respectively.

Relative growth rate (RGR)

Growth rate analysis offers critical insight into the physiological performance of chia under different weed management regimes. During crucial reproductive phase (60-90 DAS), weed-free control gave highest RGR of 0.049 g g⁻¹ day⁻¹, underscoring the significant benefits of maintaining a weed-free environment for maximizing crop biomass accumulation (Fig. 4). The effectiveness of pre-emergence sulfentrazone can be attributed to its early suppression of dominant weed flora, which reduced early-season competition and allowed better canopy establishment, a pattern similarly observed by Hasanuddin *et al.* (2022) in soybean and Karkanis *et al.* (2018) in chia under Mediterranean conditions. Interestingly, high RGR in T₂ also suggests that post-emergence application of bentazon, despite delayed application at 30 DAS, effectively reduced broadleaf weed pressure during the active vegetative-to-reproductive transition. This aligns with findings of Singh *et al.* (2019) who noted that bentazon facilitates improved plant vigour by reducing weed-crop competition for critical resources, particularly in dicot crops like potato and chia. From a physiological standpoint, the improvements in

RGR reflect an increased net assimilation rate and leaf area efficiency, both of which are essential for optimal reproductive development. Microscopic observations in bentazon-treated plots as noted by

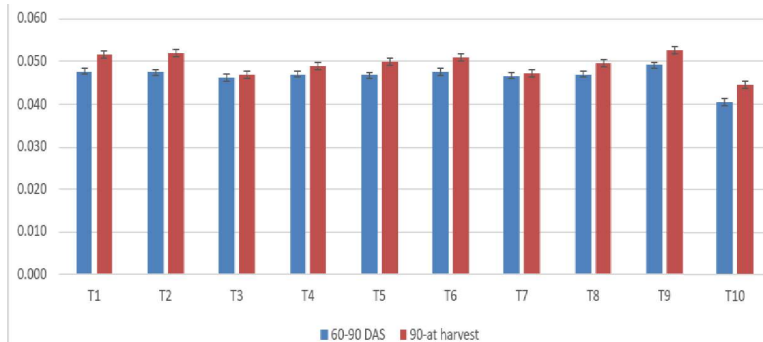


Fig. 4: Relative growth rate (g m⁻² day⁻¹) as influenced by different weed management practices in Chia

For both Fig. 5 and Fig. 6: T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - uazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluzifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ as pre-emergence; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ as pre-emergence; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ pre-emergence; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ pre-emergence; T₉ - weed free and T₁₀ - weedy check.

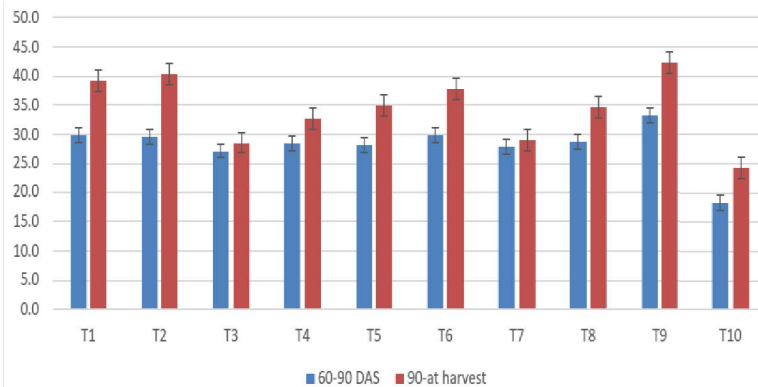


Fig. 5: Crop growth rate (CGR) as influenced by different weed management practices in Chia

were significantly higher than weedy check (T₁₀: 18.3 g m⁻² day⁻¹) [Fig. 5]. These results affirm the role of effective weed control in promoting canopy expansion and assimilate accumulation. More importantly, during reproductive to maturity phase (90 DAS-harvest), bentazon 750 g ha⁻¹ achieved a CGR of 40.4 g m⁻² day⁻¹, which was statistically equivalent to the weed-free control (42.2 g m⁻² day⁻¹) and significantly superior to all other herbicide treatments, including pre-emergence options. This superior late-season performance aligns with the enhanced yield observed in T₂ and can be attributed to the sustained photosynthetic activity and better reproductive sink development, as previously reported by Singh *et al.* (2019) in a post-emergence studies on dicot crops. The late-stage physiological advantage observed in bentazon-treated plots reflects both direct weed suppression and indirect crop stimulation effects, such as improved light interception, lower canopy stress, and more efficient translocation of assimilates to reproductive tissues. The combination of high RGR and CGR values during this period strongly correlates with yield advantage of bentazon 750 g ha⁻¹ treatment, making it a promising post-emergence weed management strategy in chia.

Weed management index (WMI) and Herbicide efficiency index (HEI)

The WMI and HEI are integrative indicators used to evaluate the overall effectiveness and economic

Kumar *et al.* (2024c, 2025) revealed enhanced lateral root proliferation and dense fine root structures, likely improving nutrient uptake and contributing to the sustained dry matter accumulation. These findings highlight that both early weed suppression (via sulfentrazone) and timely post-emergence broadleaf control (via bentazon) are critical in enhancing the physiological performance of chia. Integrating such herbicide strategies can significantly improve crop competitiveness and growth rate during most yield-sensitive stages.

Crop growth rate (CGR)

CGR analysis offers a direct measure of absolute biomass accumulation across the treatments. During the peak vegetative-to-reproductive transition phase (60-90 DAS), the weed-free treatment recorded highest CGR (33.3 g m⁻² day⁻¹), followed closely by bentazon 48% SL treatments (T₁: 29.6 and T₂: 29.9 g m⁻² day⁻¹), all of which

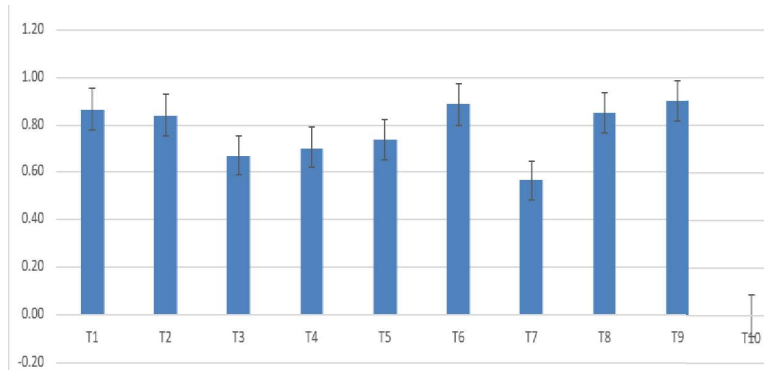


Fig. 6: Weed management index (WMI) and herbicide efficiency index (HEI) as influenced by different weed management practices in chia

For both Fig.7 and Fig. 8: T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - Fluzifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluzifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ [as pre-emergence]; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ [as pre-emergence]; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ [as pre-emergence]; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ [pre-emergence]; T₉ - weed free and T₁₀ - weedy check.

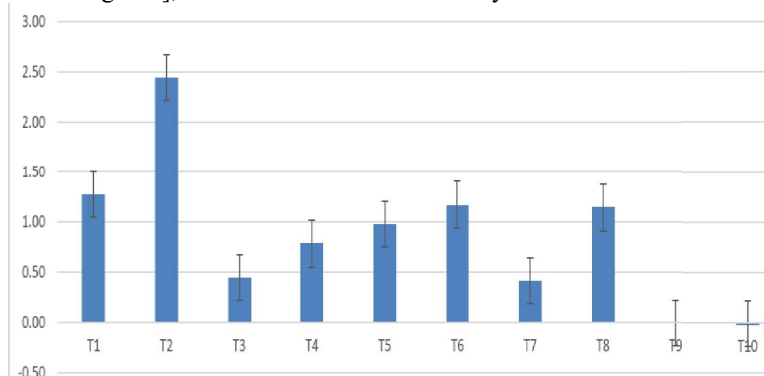


Fig. 7: Herbicide efficiency index (HEI) as influenced by different weed management practices in Chia

crop yield enhancement, aligning with the findings of Gupta *et al.* (2017) and Singh *et al.* (2019), who documented improved crop productivity in response to timely bentazon application in legume and oilseed crops. Together, these indices reaffirm that sulfentrazone @ 75 g ha⁻¹ is highly effective for early weed suppression, while bentazon @ 750 g ha⁻¹ offers season-long benefits by combining late-stage weed control with enhanced crop physiological performance and yield realization.

Seed yield

Seed yield, the ultimate indicator of weed management efficacy, revealed significant differences among the treatments (Table 1). The weed-free control gave highest seed yield of 554 kg ha⁻¹, establishing it as benchmark for optimal productivity under minimal weed competition. Among the herbicide treatments, bentazon 48% SL @ 750 g ha⁻¹ recorded second highest yield of 495 kg ha⁻¹, which accounted for 89.4% of the weed-free yield and was statistically comparable to the weed-free treatment. Following closely, sulfentrazone 39.6% SC @ 75 g ha⁻¹ produced a seed yield of 467 kg ha⁻¹ (84.3% of weed-free yield), significantly outperforming lower-dose treatments and weedy check. These two treatments were statistically superior to all other herbicidal options, indicating their strong

viability of weed control strategies. These indices provide a holistic assessment by factoring in both weed suppression efficacy and resulting crop performance. In present study, sulfentrazone 39.6% SC @ 75 g ha⁻¹ showed highest WMI (0.89) among all herbicide treatments (Fig. 6) - statistically comparable to the weed-free control (0.90). This indicates that the treatment provides consistent and season-long suppression of dominant weed flora with minimal regrowth, a finding corroborated by Karkanis *et al.* (2018) and Hasanuddin *et al.* (2022), who reported prolonged efficacy of sulfentrazone in dicot crops under semi-arid and arid climates. In contrast, bentazon 48% SL @ 750 g ha⁻¹ (T₂) exhibited highest HEI value (2.45), significantly higher than all other treatments (Fig. 7). This reflects its exceptional capacity to translate weed control into tangible yield gains, particularly under late-season competitive stress. The superior HEI of T₂ underscores its dual role in effective broadleaf weed suppression and

weed suppression capacity and positive influence on crop productivity. In contrast, weedy check showed lowest yield (291 kg ha⁻¹), highlighting the detrimental effect of uncontrolled weed competition,

Table 1: Dry biomass, seed and straw yield and harvest index of chia as influenced by herbicide application

Treatments	Seed yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Biomass yield (kg ha ⁻¹)	Harvest index (%)
Bentazon 48% SL [500 g ha ⁻¹ at 30 DAS]	469	194	730	64.20
Bentazon 48% SL [750 g ha ⁻¹ at 30 DAS]	495	197	755	65.56
Fluazifop-p-butyl 11.1% SL [100 g ha ⁻¹ at 30 DAS]	382	175	610	62.60
Fluazifop-p-butyl 11.1% SL [200 g ha ⁻¹ at 30 DAS]	417	196	674	62.64
Sulfentrazone 39.6% SC [50 g ha ⁻¹ as pre-emergence]	434	194	697	62.18
Sulfentrazone 39.6% SC [75 g ha ⁻¹ as pre-emergence]	467	198	712	65.57
Pendimethalin 38.7% CS [200 g ha ⁻¹ pre-emergence]	371	177	598	62.12
Pendimethalin 38.7% CS [400 g ha ⁻¹ pre-emergence]	460	195	705	65.30
Weed free control	554	223	826	67.01
Weedy check	291	161.4	512.0	56.76
SEM±	25.65	9.20	32.97	3.59
CD _{0.05}	76	27	98	ns

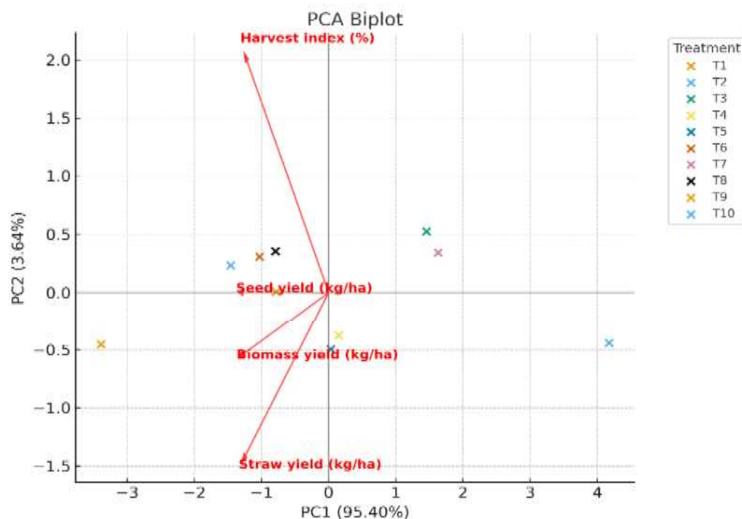


Fig. 8: Principal component analysis (PCA) of yield parameters of chia as influenced by different weed management practices; T₁ - Bentazon 48% SL @ 500 g ha⁻¹ at 30 DAS; T₂ - Bentazon 48% SL @ 750 g ha⁻¹ at 30 DAS; T₃ - Fluazifop-p-butyl 11.1% SL @ 100 g ha⁻¹ at 30 DAS; T₄ - Fluazifop-p-butyl 11.1% SL @ 200 g ha⁻¹ at 30 DAS; T₅ - Sulfentrazone 39.6% SC @ 50 g ha⁻¹ [as pre-emergence]; T₆ - Sulfentrazone 39.6% SC @ 75 g ha⁻¹ [as pre-emergence]; T₇ - Pendimethalin 38.7% CS @ 200 g ha⁻¹ [as pre-emergence]; T₈ - Pendimethalin 38.7% CS @ 400 g ha⁻¹ [pre-emergence]; T₉ - weed free and T₁₀ - weedy check.

application of bentazon 48% SL @ 750 g ha⁻¹ provides effective season-long control, particularly during the reproductive phase of crop. This integrated herbicide schedule effectively mitigates both early and late-season weed interference, ensuring consistent improvements in crop growth, biomass accumulation, and seed yield. The study highlights that strategic herbicide integration can enhance seed yield by 30-50% over weedy controls, with weed-free treatment giving highest yield (554 kg ha⁻¹). Notably, higher herbicide doses consistently demonstrated improved efficacy, validating the need for dose optimization under field conditions. These findings offer practical and economically

weed competition, which led to an estimated yield loss of 47.5% as compared to the weed-free condition. These findings are in agreement with Gupta *et al.* (2017) and Kumar *et al.* (2024a,b) who observed similar trends in yield reductions due to weed interference and recovery with timely and effective herbicidal interventions.

Conclusions: The study demonstrated that a pre-emergence application of either sulfentrazone 39.6% SC @ 75 g ha⁻¹ or pendimethalin 38.7% CS @ 400 g ha⁻¹ is critical for early-season weed suppression, enabling chia to establish a competitive canopy during its vulnerable initial growth phase. When broadleaf weed pressure persists, a post-emergence

viable solutions for commercial chia production in arid and semi-arid agro-ecologies, contributing to sustainable intensification of niche crops through science-based weed management practices.

Conflict of interest: The authors declare that they have no known competing personal relationships that could influence the research work reported in this paper.

Acknowledgements: The authors acknowledge Agricultural University, Jodhpur for providing setup for carrying out the work.

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