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RESEARCH ARTICLE

Optimising weed control in sesame: insights into herbicide performance and crop productivity

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Abstract

Sesamum indicum L., a crucial oilseed crop in tropical and subtropical regions, is highly susceptible to weed competition during its early growth stages, leading to significant yield losses. This study aimed to evaluate the efficacy of various pre-emergence (PE) and early post-emergence (EPoE) herbicides in weed management under rainfed conditions. Field experiments were conducted in 2022 and 2023 using a randomised complete block design with thirteen treatments. Results indicated that the PE application of pendimethalin 30 % EC at 0.75 kg ha^{-1} effectively reduced weed density and dry weight, achieving a weed control efficiency of 73.5 % without phytotoxic effects on the crop. While metribuzin and diuron exhibited high weed control, their severe phytotoxicity rendered them unsuitable. Hand weeding at 20 and 40 DAS demonstrated superior weed suppression but was less practical due to labour intensity. Pendimethalin-treated plots recorded significantly higher leaf area index, dry matter accumulation and nutrient uptake, leading to improved yield attributes. Seed yield losses were minimised by 74.6 % compared to the weedy check, with pendimethalin providing a high benefit-cost ratio of 2.92. Correlation analysis revealed a strong negative relationship between weed biomass and crop yield, highlighting the role of effective weed control in nutrient management. These findings underscore the potential of pendimethalin as a sustainable and economical herbicide for optimising sesame productivity.

Keywords: herbicides; phytotoxicity; sesame; weed management

Introduction

Sesame (*Sesamum indicum* L.) holds significant importance in semi-tropical and tropical agricultural systems, serving as a readily available and highly nutritious source of food for both humans and animals. This ancient oilseed crop, commonly known as the "queen of oilseeds", has been grown for centuries due to its remarkable ability to thrive in diverse environments and outstanding nutritional benefits. It is primarily cultivated for its valuable seeds, which contain approximately 56.49 - 59.97 % oil, 18.92 - 23.18 % protein and 18.2 - 20.2 % carbohydrates, making it an essential component of both traditional diets and modern food industries (1, 2). Global sesame seed production in 2022 was approximately 6.74 million tons, harvested from around 12.8 million ha (3), underscoring its economic importance in the agricultural sector, particularly in developing countries.

Weeds pose a significant biological threat to agricultural systems, capable of causing substantial damage to both cropped and non-cropped areas. Their presence not only reduces the quality of produce but also increases production costs, as they often require significant effort and resources to manage. Weeds frequently serve as alternative hosts for insect pests and diseases, further complicating crop management practices (4, 5). Weed infestation stands out as one of the most critical biotic stresses affecting sesame cultivation, significantly reducing both yield and quality. The relatively slow initial growth of sesame, coupled with its limited competitive ability, makes it particularly vulnerable to weed competition during the initial 4 weeks after sowing (6). During this critical period, unchecked weed growth can lead to substantial competition for essential resources such as light, water and nutrients, severely limiting the crop's ability to establish and thrive.

Delayed or inadequate weed control in sesame fields often results in significant yield losses, emphasising the need for effective and timely weed management strategies. Yield losses due to weeds in sesame can be substantial, with reported figures ranging from 30 % to as high as 75 %, depending on the severity of infestation and the weed species involved (7, 8). Critical weeding periods have been identified as 30 days after sowing (DAS) in India and 15 - 45 DAS in Madhya Pradesh, India (9, 10). These variations in the critical period for weed control (CPWC) are influenced by factors such as weed species composition, ground cover, local climatic conditions and cultural practices (11). Weeds such as grasses, sedges and broadleaf species tend to dominate sesame fields and their competition can lead to a significant reduction in yield potential.

In addition to competing for space and resources, weeds exacerbate the challenges of sesame cultivation, particularly because the crop is often grown on marginal soils with low fertility. In such conditions, competition for soil-applied fertilisers becomes particularly intense, further impacting crop growth and productivity. Effective weed management, therefore, is essential to ensure that weeds do not outcompete sesame for nutrients and other critical resources. Farmers in India and other developing nations traditionally rely on mechanical and manual weeding methods, such as hand hoeing, to control weeds in sesame fields. Although effective, these methods require substantial labour, time and financial investment (12). Additionally, adverse weather conditions, including extended rainfall or drought, along with labour shortages during peak farming seasons, further limit their feasibility and dependability.

Given these limitations, herbicidal weed management has gained popularity as a viable alternative among farmers. Herbicides provide a fast and economical solution for managing diverse weed populations, proving especially effective during the crop's crucial early growth phases. The application of pre-emergence (PE) and early post-emergence (EPoE) herbicides has been shown to significantly reduce weed competition during these critical stages, creating a weed-free environment that is conducive to sesame establishment and growth (13). Herbicide efficacy is influenced by several factors, including application rate, timing, environmental conditions and the specific weed flora present in the field. Therefore, integrating chemical weed management with sustainable agronomic practices is crucial for enhancing sesame productivity while minimising environmental impacts.

To address this, a study was undertaken to evaluate the effectiveness of chemical weed management in sesame cultivation, with an emphasis on comparing the performance of pre-emergence and early post-emergence herbicides in controlling diverse weed species commonly found in sesame fields, such as *Echinochloa colona*, *Cyperus rotundus*, *Digera arvensis*, *Commelina benghalensis* and *Amaranthus viridis*. Pre-emergence application of pendimethalin at 1.0 kg ha^{-1} has been reported to effectively suppress annual grasses and broadleaf weeds such as *Digitaria sanguinalis* and *Amaranthus spp.*, contributing to reduced weed competition during early crop establishment (14). Similarly, early post-emergence application of quizalofop-ethyl at 50 g ha^{-1} has demonstrated high efficacy against narrow-leaved grassy weeds like *E. colona*, resulting in significant weed population reduction in summer sesame (15).

The results are expected to provide valuable insights into developing effective, economical and environmentally sustainable weed control strategies for sesame cultivation, ensuring higher yields and better resource utilisation for farmers.

Materials and Methods

Experimental site

Two field experiments were conducted under rainfed condition at the research field unit of All India Coordinated Research Project (AICRP) on Weed Management, University of Agricultural Sciences, Gandhi Krishi Vignana Kendra, Bengaluru, Karnataka (13˚ 08’ N Latitude and 77˚ 57’ E Longitude, at an altitude of 924 Mean Sea Level (MSL)) during *kharif* of 2022 and 2023. Meteorological data at the experimental site during the sesamum growing seasons in 2022 and 2023 are presented in Table 1. The experimental field had a sandy loam soil texture, was deep and gently sloped, ensuring effective drainage. It was characterised by a slightly acidic nature with a pH of 6.58. The soil exhibited lower levels of soil organic carbon (0.35 %) and available nitrogen (274.1 kg ha^{-1}), while available P_2O_5 (26.72 kg ha^{-1}) and K_2O (191.5 kg ha^{-1}) were found to be moderate.

Experimental design

The experiment was laid out in a randomised complete block design (RCBD) with 3 replications, utilising naturally occurring weed populations. A total of 13 treatments were evaluated in the study (Table 2). Herbicidal treatments consisted of pre-emergent (PE) application of T_1: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_2: Oxadiargyl 80 % WP at 30 g a.i. ha^{-1}; T_3: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_4: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_5: Alachlor 50 % EC at 1000 g a.i. ha^{-1}

Table 2. Herbicides used for weed control in sesame in 2022 and 2023

Common Name	Application rate (g a.i. ha^{-1})	Trade name	Application timing
Metribuzin	300	Secncor 75 WP	PE and EPoE
Oxadiargyl	30	Topstar 80 WP	PE
Pendimethalin	750	Stomp 30 EC	PE and EPoE
Pendimethalin	1000	Stomp 30 EC	PE and EPoE
Alachlor	1000	Lasso 50 EC	PE
Diuron	1000	Direx 80WP	EPoE
Quizalofop ethyl	60	Targa Super 5 EC	EPoE
Inter-cultivation *fb* hand weeding			35 DAS
Weed-free check	-	-	Hand weeding at 20 and 40 DAS
Weedy check	-	-	-

EC = emulsifiable concentrate. WP = wettable powder. PE = Pre-emergence application of herbicide. EPoE = Early post-emergence application at the 2-4 leaf stage of the weeds.

Table 1. Meteorological data at the experimental site during the sesamum growth period in 2022 and 2023

Month	Temperature (°C)						Total precipitation (mm)		Pan evaporation (mm)		Bright sunshine hours	
	2022			2023								
	Max.	Min.	Mean	Max.	Min.	Mean	2022	2023	2022	2023	2022	2023
July	27.3	19.1	23.2	28.3	19.6	24.0	149.8	115.2	3.1	3.1	3.4	3.3
August	27.4	18.9	23.2	30.5	20.2	25.4	211.4	25.80	4.1	7.2	3.2	5.3
September	27.7	18.9	23.3	29.3	19.8	24.6	142.0	194.0	4.6	5.7	3.6	3.8
October	27.0	18.3	22.7	30.1	19.5	24.8	361.0	67.6	4.7	7.3	3.3	4.3
November	26.0	16.7	21.4	29.2	18.8	24.0	30.00	154.2	5.3	5.8	3.4	3.7

and early post-emergent (EPoE) application of T_6: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_7: Diuron 80 % WP at 1000 g a.i. ha^{-1}; T_8: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_9: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}; T_{10}: Quizalofop ethyl 5 % EC at 60 g a.i. ha^{-1}; T_{11}: Inter-cultivation at 35 DAS *fb* hand weeding as farmer's practice; T_{12}: Hand weeding at 20 and 40 DAS and T_{13}: Unweeded control (weedy check). Treatment T_{12} was considered a standard check to represent an ideal weed control condition and was considered weed-free solely for calculation purposes to evaluate the comparative efficacy of different weed management treatments. In weed-infested plots, weeds were permitted to compete with sesame for the entire growing season. Herbicide applications were carried out using a backpack sprayer fitted with hydraulic flat fan nozzles, with spray volumes of 750 L/ha for pre-emergent and 500 L/ha for early post-emergent herbicides. All PE herbicides were applied the day after sowing, whereas all EPoE herbicides were applied at the 20 DAS. In the hand-weeding treatment plots, weeds were removed manually using *varvari* tools, following the specified treatment schedule.

Crop management practices

The experimental field was prepared using tractor-drawn equipment, involving ploughing, followed by 2 harrowings and final levelling to ensure a uniform seedbed. Each treatment plot measured 4.5 m × 3.6 m. Seeds of *Sesamum indicum* cv. GKVKS-1 were dibbled in rows spaced 30 cm apart, maintaining a plant-to-plant distance of 10 cm, with 2 seeds sown per hill to ensure optimal germination. The crop was fertilised with 37.5:25:25 kg N-P_2O_5-K_2O per ha at sowing, using urea, single super phosphate and muriate of potash. The entire dose of all fertiliser was applied as a basal application. Sowing was conducted on June 29, 2022 and July 16, 2023, for the 2-year study.

Weed studies

Weed observations in the sesame under various treatments were recorded at 15 and 30 days after sowing (DAS) and at harvest, using a 0.25 m^2 quadrat placed in 4 locations within each plot. Individual weeds were collected from the same area during each observation. The weed samples were dried in an oven at 60 ± 2 °C until they reached a constant weight before weighing. The data on weed density and dry weight were subjected to square root transformation ($\sqrt{x} + 0.5$) before analysis. Several weed indices were calculated using the following equations. Relative weed density, weed control efficiency (WCE) was computed by using the following formula (16, 17):

Relative weed density =

$$\frac{\text{No. of individual of same species}}{\text{No. of individuals of all species}} \times 100 \quad \text{(Eqn. 01)}$$

Weed control efficiency =

$$\frac{\text{Dry weight (g) of weeds in weedy check-Dry weight (g) of weeds in the treated plot}}{\text{Dry weight (g) of weeds in the treated plot}} \times 100 \quad \text{(Eqn. 02)}$$

Weed Index (WI)

The weed index quantifies the yield reduction caused by weed competition relative to weed-free plots. It is determined using the following equation (14):

Weed index =

$$\frac{\text{Seed yield from the weed free plot - Seed yield from the treated plot}}{\text{Seed yield from the weed free plot}} \times 100 \quad \text{(Eqn. 03)}$$

Treatment efficiency index (TEI)

This index assesses the effectiveness of herbicides in weed control and their phytotoxic effects on the crop, calculated using the following formula (18).

Treatment Efficiency index =

$$\frac{\dfrac{\text{Yield of treated plot - Yield of unweeded plot}}{\text{Yield of unweeded plot}}}{\left(\dfrac{\text{Weed dry weight in the treated plot}}{\text{Weed dry weight in unweeded plot DWc}}\right)} \quad \text{(Eqn. 04)}$$

Weed persistence index (WPI)

This index represents weed resistance to the tested treatments and evaluates the effectiveness of the selected herbicides, calculated using the following formula (19):

WPI =

$$\frac{\text{Weed biomass of treated plot}}{\text{Weed biomass of control plot}} \times \frac{\text{Weed count of control plot}}{\text{Weed count of Treated plot}} \quad \text{(Eqn. 05)}$$

Crop resistance index (CRI)

This index represents the relationship between the proportional increase in crop biomass and the proportional reduction in weed biomass in treated plots, calculated using the following formula (19):

CRI =

$$\frac{\text{Biomass of crop in Treated plot}}{\text{Biomass of crop in Control plot}} \times \frac{\text{Biomass of weed control plot}}{\text{Biomass of weed treated plot}} \quad \text{(Eqn. 06)}$$

Weed management index (WMI)

This index quantifies the yield improvement relative to the control as a result of weed management, determined by the percentage of weed control achieved by the respective treatment, using the following formula (19):

$$\text{WMI} = \frac{\text{Percent yield increase over control}}{\text{Percent control of weeds}} \quad \text{(Eqn. 07)}$$

Agronomic management index (AMI)

It is a comprehensive tool that evaluates the effectiveness of various agronomic practices in improving crop productivity, resource use efficiency and sustainability (19):

$$\text{AMI} = \frac{\text{Percent yield increase - percent control of weeds}}{\text{Percent control of weeds}} \qquad \text{(Eqn. 08)}$$

Phytotoxicity observations on sesame plants were recorded 15 days after herbicide application (DAA) using the phytotoxicity rating scale (20). The level of phytotoxicity was visually assessed based on the crop's response and rated on a scale from 0 to 10, where 0 indicated no harmful effect of the herbicide on sesame and 10 represented complete death of the sesame plants due to the herbicide.

Growth and yield studies

Growth observations were taken from the third row on both sides of the plot, designated as the sampling row. The green leaves from 5 randomly selected plants were collected and analysed using a leaf area meter at 30, 60 DAS and at harvest to determine the leaf area. The leaf area per plant was recorded and expressed as cm^2 per plant. Leaf area index (LAI) was calculated at 30, 60 DAS and harvest as per the formula (21):

$$\text{Leaf Area Index} = \frac{\text{Leaf area per plant}}{\text{Spacing}} \qquad \text{(Eqn. 09)}$$

The remaining samples were sun-dried for 24 hr, followed by oven-drying for 48 hr to determine dry matter (g $plant^{-1}$). Leaf area duration (days) and crop growth rate (g m^{-2} day^{-1}) were calculated using the following formula (22). Leaf area duration quantifies the capacity of a crop to maintain leaf area per unit of land over its growth period.

$$\text{Leaf Area Duration} = \frac{LAI_1 + LAI_2}{2} \times (t_2 - t_1) \qquad \text{(Eqn. 10)}$$

Where, LAI_1 = Leaf area index at time t_1

LAI_2 = Leaf area index at time t_2

$$\text{Crop growth rate} = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{A} \qquad \text{(Eqn. 11)}$$

Where, W_1 = Total dry matter at time t_1

W_2 = Total dry matter at time t_2

A = Area occupied by plants

The number of capsules per plant was recorded at harvest from 5 randomly selected plants. The seed and stalk yield of sesame was recorded at harvest from the net plot by threshing manually, then the yield was converted from kg $plot^{-1}$ to t ha^{-1} by multiplying with the appropriate conversion factor. An economic analysis of treatments was conducted on a per-hectare basis, with cultivation costs calculated based on labour and the market prices of various common and variable agro-inputs associated with sesame cultivation across different treatments. Gross monetary returns were determined using the market prices for sesame, which were Rs. 160 kg^{-1} and Rs. 175 kg^{-1} in 2022 and 2023, respectively and the benefit-cost ratio (B:C) was computed.

Nutrient uptake studies

Grain, straw and weed samples collected at harvest underwent acid digestion for the determination of total N, P and K content using the micro-Kjeldahl method, the vanado-molybdate yellow colour method and flame emission photometry respectively (23, 24). NPK uptake by sesame plants and weeds was calculated by multiplying the nutrient content by their respective dry matter production and expressed in kg ha^{-1}.

Nutrient uptake (kg/ha) =

Nutrient content (%) x crop yield dry matter (kg/ha)

(Eqn. 12)

Statistical studies

The data collected on various parameters during the study were statistically analysed using OPSTAT software. However, due to high variability in weed density and biomass data, a square root transformation was applied before performing the analysis of variance (ANOVA) (25). The standard error of the mean was calculated for each parameter and the critical difference was determined only for statistically significant results at the 0.05 probability level. Additionally, Pearson correlation and regression analyses were performed using Microsoft Excel 2019.

Results and Discussion

Weed flora distribution

Weeds exhibit stronger competition during their early growth stages compared to later, with their growth being more vigorous and rapid than that of the desired crop plants (26). The experimental field was predominantly infested with sedges like *C. rotundus* (0.03 %) and various grassy weeds (29.07 %), including *Eleusine indica, E. colona, Dactyloctenium aegyptium, Digitaria marginata and Cynodon dactylon.* Broadleaved weeds were even more prevalent, constituting 70.4 % of the total weed flora at harvest. The prominent broadleaved weeds included *Borreria hispida, Ageratum conyzoides, Commelina benghalensis, Lonaidium sufruiticesum, Celosia argentea, Argemone mexicana, Acanthospermum hispidum, Cleome viscosa, Achyranthes aspera, Oldenlandia corymbosa and Blainvillea acmella.* In total, 17 major weed species were identified infesting the field, with those from the families Amaranthaceae and Poaceae being dominant throughout the growth period. Broadleaved weeds, particularly *Celosia argentea* (35.28 %), *A. aspera* (16.33 %) and *B. hispida* (12.14 %) dominated the field at all growth stages (Fig. 1).

Effect of different weed management treatments on weed density and weed dry weight

Data in Table 3 and 4 indicate that weed management practices significantly reduced weed population and dry weight in sesame at 15 and 30 DAS and at harvest, compared to the untreated weedy check. The application of metribuzin

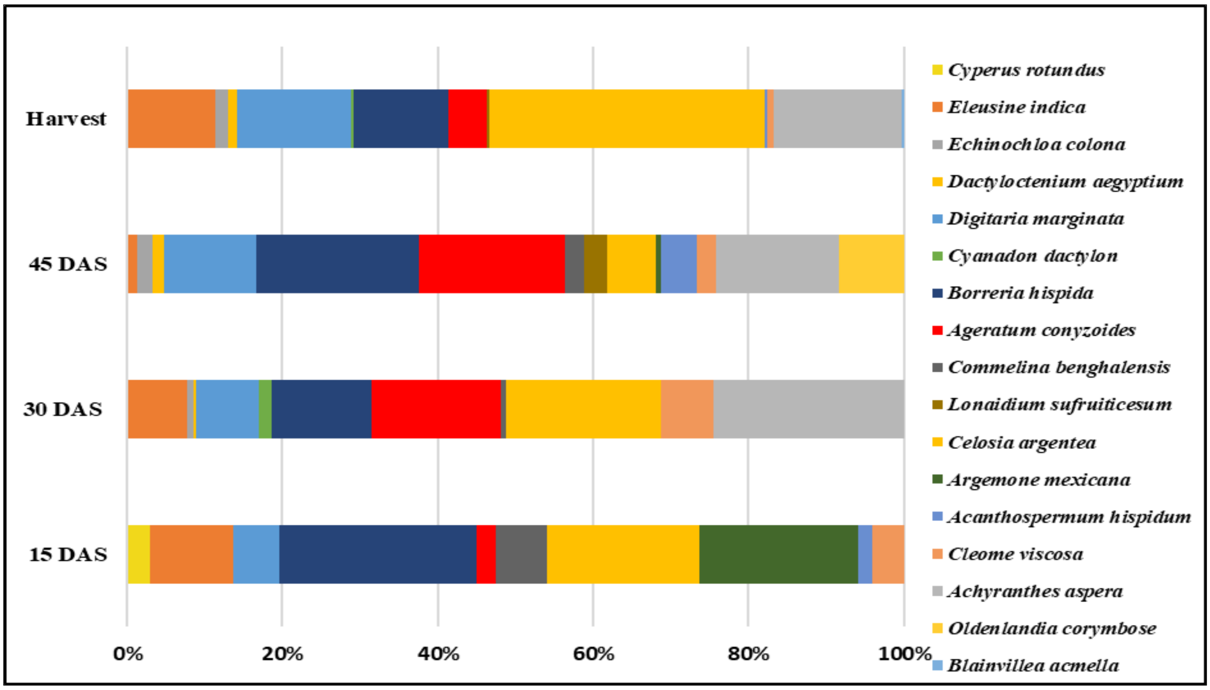

Fig. 1. Relative weed density (%) of different weed species infested in the weedy check (pooled data over 2 years).

Table 3. Effect of weed management practices on weed density at 15, 30 DAS and at harvest in sesame (pooled data over 2 years)

Treatments	Weed density (no./m²)					
	Grasses			Broad-leaved weeds		
	15 DAS	30 DAS	Harvest	15 DAS	30 DAS	Harvest
T_1	1.32^{a} (2.00)	2.19^{abc} (4.50)	4.27^{cd} (19.66)	1.74^{a} (4.67)	4.76^{b} (24.00)	7.18^{bcde} (51.33)
T_2	1.00^{a} (0.67)	2.35^{bc} (5.00)	3.99^{cd} (16.66)	2.28^{a} (9.67)	5.84^{bc} (34.33)	7.60^{bcde} (57.83)
T_3	1.57^{a} (2.33)	0.71^{a} (0.00)	1.67^{b} (3.33)	6.10^{b} (36.67)	7.32^{cdef} (56.00)	8.60^{def} (74.66)
T_4	1.71^{ab} (3.00)	0.71^{a} (0.00)	1.34^{b} (1.33)	5.81^{b} (33.33)	7.29^{cdef} (53.00)	8.60^{ef} (74.00)
T_5	1.18^{a} (1.33)	1.74^{abc} (4.67)	1.64^{b} (2.33)	5.92^{b} (34.67)	6.83^{cde} (47.33)	8.62^{ef} (74.00)
T_6	3.16^{b} (10.33)	0.71^{a} (0.00)	5.59^{de} (31.00)	6.16^{b} (38.00)	0.71^{a} (0.00)	4.57^{a} (21.00)
T_7	1.94^{ab} (4.33)	1.10^{ab} (1.00)	3.48^{bcd} (12.00)	6.39^{b} (40.67)	0.71^{a} (0.00)	6.40^{b} (41.66)
T_8	2.11^{ab} (4.00)	2.18^{abc} (4.67)	3.58^{bcd} (14.00)	6.24^{b} (39.67)	4.08^{b} (16.67)	7.59^{bcde} (57.66)
T_9	1.94^{ab} (4.00)	2.73^{cd} (7.67)	3.23^{bc} (11.66)	5.72^{b} (32.67)	5.95^{bcd} (35.33)	7.22^{bcde} (52.33)
T_{10}	2.54^{ab} (6.00)	0.71^{a} (0.00)	2.12^{bc} (5.00)	6.57^{b} (43.33)	7.77^{def} (60.00)	9.82^{f} (97.00)
T_{11}	2.38^{ab} (5.33)	4.02^{de} (16.33)	3.02^{bc} (10.33)	6.73^{b} (45.33)	8.42^{ef} (70.67)	8.55^{cdef} (73.33)
T_{12}	3.18^{b} (9.67)	1.48^{abc} (2.00)	3.38^{bc} (11.00)	6.59^{b} (43.00)	5.65^{bc} (31.67)	7.16^{bcde} (51.00)
T_{13}	3.13^{b} (9.33)	4.18^{e} (18.33)	6.44^{e} (41.33)	6.74^{b} (45.00)	9.00^{f} (81.67)	9.87^{f} (98.00)
SEm ±	**0.45**	**0.47**	**0.67**	**0.61**	**0.59**	**0.43**
C.D. at 5 %	**1.32**	**1.37**	**1.95**	**1.79**	**1.72**	**1.27**

Figures in parentheses indicate original value; data analysed using square root transformation= $\sqrt{(x + 0.5)}$; Common letters are non-significant according to Duncan's multiple range test where $p < 0.05$; T1: Metribuzin 70 % WP at 300 g a.i. ha-1; T2: Oxadiargyl 80 % WP at 30 g a.i. ha-1; T3: Pendimethalin 30 % EC at 750 g a.i. ha-1; T4: Pendimethalin 30 % EC at 1000 g a.i. ha-1, T5: Alachlor 50 % EC at 1000 g a.i. ha-1 and early post-emergent (EPoE) application of T6: Metribuzin 70 % WP at 300 g a.i. ha-1; T7: Diuron 80 % WP at 1000 g a.i. ha-1; T8: Pendimethalin 30 % EC at 750 g a.i. ha-1; T9: Pendimethalin 30 % EC at 1000 g a.i. ha-1, T10: Quizalofop ethyl 5 % EC at 60 g a.i. ha-1; T11: Inter-cultivation at 35 DAS *fb* hand weeding; T12: Hand weeding at 20 and 40 DAS and T13: weedy check.

Table 4. Effect of weed management practices on total weed dry weight at 15, 30 DAS and at harvest in sesame (pooled data over 2 years)

Treatments	Total weed dry weight (g/m²)					
	Grasses			Broad-leaved weeds		
	15 DAS	30 DAS	Harvest	15 DAS	30 DAS	Harvest
T_1	0.78^{a} (0.11)	1.63^{a} (2.44)	4.69^{cd} (26.65)	0.80^{a} (0.16)	2.63^{bc} (6.89)	7.29^{abc} (56.65)
T_2	0.77^{a} (0.11)	1.65^{a} (2.42)	4.53^{cd} (29.93)	0.82^{a} (0.19)	2.57^{bc} (6.39)	10.05^{cd} (102.3)
T_3	0.78^{a} (0.11)	0.71^{a} (0.00)	0.95^{d} (0.43)	1.09^{a} (0.70)	3.77^{cd} (15.4)	8.67^{bcd} (76.07)
T_4	0.79^{a} (0.13)	0.71^{a} (0.00)	1.07^{a} (0.66)	1.10^{a} (0.73)	4.33^{d} (18.53)	9.67^{cd} (93.38)
T_5	0.75^{a} (0.07)	1.57^{a} (3.45)	1.16^{ab} (0.86)	1.14^{a} (0.82)	3.56^{cd} (13.08)	8.66^{bcd} (74.98)
T_6	0.90^{a} (0.31)	0.71^{a} (0.00)	4.24^{bcd} (18.02)	1.65^{ab} (2.23)	0.71^{a} (0.00)	5.63^{ab} (35.16)
T_7	0.98^{a} (0.47)	1.36^{a} (2.20)	7.15^{d} (54.68)	1.50^{c} (1.74)	0.71^{a} (0.00)	4.53^{a} (27.85)
T_8	0.95^{a} (0.44)	1.12^{a} (0.82)	4.07^{abc} (17.68)	1.63^{c} (2.17)	1.81^{ab} (3.04)	7.37^{abc} (54.96)
T_9	0.91^{a} (0.34)	1.09^{a} (0.72)	3.66^{abc} (15.83)	1.62^{c} (2.12)	2.02^{ab} (3.78)	8.44^{bcd} (71.29)
T_{10}	0.82^{a} (0.17)	0.71^{a} (0.00)	1.36^{ab} (1.82)	1.69^{c} (2.36)	4.07^{d} (16.26)	11.63^{de} (137.6)
T_{11}	0.90^{a} (0.34)	3.27^{a} (11.57)	2.18^{abc} (4.70)	1.64^{c} (2.29)	7.26^{e} (52.28)	7.01^{abc} (48.98)
T_{12}	0.93^{a} (0.37)	0.99^{a} (0.56)	2.08^{abc} (3.88)	1.59^{c} (2.09)	1.98^{ab} (3.60)	4.77^{a} (22.37)
T_{13}	1.28^{b} (1.15)	3.60^{b} (12.57)	3.31^{abc} (11.17)	1.43^{bc} (1.55)	7.23^{e} (52.47)	13.34^{e} (178.3)
SEm ±	**0.07**	**0.42**	**0.93**	**0.10**	**0.45**	**1.00**
C.D. at 5 %	**0.19**	**1.23**	**2.73**	**0.29**	**1.32**	**2.93**

Figures in parentheses indicate original value; data analysed using square root transformation= $\sqrt{(x + 0.5)}$; Common letters are non-significant according to Duncan's multiple range test where $p < 0.05$; T_1: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_2: Oxadiargyl 80 % WP at 30 g a.i. ha^{-1}; T_3: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_4: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_5: Alachlor 50 % EC at 1000 g a.i. ha^{-1} and early post-emergent (EPoE) application of T_6: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_7: Diuron 80 % WP at 1000 g a.i. ha^{-1}; T_8: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_9: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_{10}: Quizalofop ethyl 5 % EC at 60 g a.i. ha^{-1}; T_{11}: Inter-cultivation at 35 DAS *fb* hand weeding; T_{12}: Hand weeding at 20 and 40 DAS and T_{13}: weedy check.

70 % WP at 300 g ha^{-1} effectively minimised weed interference, leading to substantial reductions in the density and dry weight of broad-leaved weeds by 89.62 % and 89.67 % at 15 DAS and by 70.61 % and 86.86 % at 30 DAS respectively relative to the weedy check. Similar reductions in the growth of grassy weeds were recorded in the pre-emergent application of oxadiargyl 80 % WP at 30 g ha^{-1}, pendimethalin 30 % EC at 750 g ha^{-1}, alachlor 50 % EC at 1000 g ha^{-1} ranging from 75.02-92.81 % and 90.43-93.31 % in weed density and dry weight at 15 DAS, respectively. However, metribuzin 70 % WP at 300 g ha^{-1} when applied as both pre-emergence (PE) and early post-emergence (EPoE), as well as diuron 80 % WP at 1000 g ha^{-1} (EPoE), caused severe phytotoxic effects on sesame, leading to complete crop mortality. Apart from these treatments pre-emergent herbicide application of pendimethalin 30 % EC at 750 g ha^{-1} effectively managed the associated weed flora (grasses and broad-leaved weeds) as it recorded 44.01 % and 60.4 % lower total weed density and weed dry weight respectively at harvest without any phytotoxic effect on the crop, but was markedly higher than weed-free check.

Effect of different weed management treatments on weed control efficiency, weed index and agronomic indices in sesame

The weed control efficiency (WCE) was significantly higher in the weed-free check at all crop growth stages, with values exceeding 85.9 % compared to the weedy check (Table 5). Amongst different herbicide treatments, the superior WCE was with the application of metribuzin 70 % WP at 300 g ha^{-1} as PE (83.2 %) and EPoE (100 %), respectively. Whereas, pendimethalin 30 % EC at 750 g ha^{-1} as PE recorded weed control efficacy of 73.5 %, surpassing other treatments, as against 93.6 % in weed-free treatment at 30 DAS without any phytotoxic effects on the crop. In general, the WCE was highest during the early crop growth stages and lowest at harvest across all treatments, due to the emergence of new weed flushes in the later stages of the crop. Weed growth was effectively suppressed during the crop growth period with the first two flushes using hand weeding at 20 and 40 DAS in the weed-free check. Using pre-emergent pendimethalin 30 % EC at 750 g ha^{-1} has reduced weed growth by inhibiting metabolic activities, resulting in weed mortality, a weed-free and conducive environment for sesame crops, indicating improved weed control efficiency. These appear to be the most dramatic reasons for accumulating decreased dry weight of weeds. Similar findings of the higher WCE by pre-emergent herbicide application of pendimethalin in sesame are also reported (27, 28).

The weedy check treatment recorded the highest weed index, as it allowed weeds to establish freely, resulting in an 81 % seed yield loss in sesame. This was followed by quizalofop ethyl 5 % EC at 60 g ha^{-1}, which caused a 79.9 % yield loss. Pendimethalin 30 % EC at 750 g ha^{-1} emerged as the most effective treatment with respect to weed index, causing only a 20.5 % yield loss, followed by alachlor 50 % EC

Table 5. Effect of weed management practices on weed control efficiency, herbicide efficiency index, weed index and phytotoxicity of sesame (pooled data over 2 years)

Treatments	WCE (%)			TEI	WI (%)	WPI	CRI	WMI	AMI
	15 DAS	30 DAS	Harvest						
T_1	83.2	86.0	54.6	-2.22	-	0.89	0.00	-1.83	-2.83
T_2	75.0	85.7	29.2	0.57	73.4	1.32	1.80	1.36	0.36
T_3	70.6	73.5	60.3	8.03	20.5	0.71	7.47	5.25	4.25
T_4	64.6	68.7	48.7	3.55	46.3	0.94	4.43	3.74	2.74
T_5	67.3	70.3	58.7	6.82	27.6	0.75	6.51	4.76	3.76
T_6	7.1	100	73.6	-3.79	-	0.71	0.00	-1.36	-2.36
T_7	11.2	93.8	60.3	-2.58	-	1.03	0.00	-1.66	-2.66
T_8	5.7	93.7	62.2	2.49	63.1	0.73	4.78	1.51	0.51
T_9	8.0	93.0	52.8	1.50	67.5	0.99	3.41	1.34	0.34
T_{10}	7.4	73.5	24.2	0.07	79.9	1.02	1.48	0.22	-0.78
T_{11}	3.7	1.9	71.0	8.00	36.7	0.48	8.51	3.27	2.27
T_{12}	6.7	93.6	85.9	30.17	-	0.32	23.96	4.95	3.95
T_{13}	0.0	0.0	0.0	0.0	81.0	1.00	1.00	0.00	0.00

'-' indicates data not available due to complete crop phytotoxicity; **DAS=** Days after sowing; **DAA**= Days after application; T_1: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_2: Oxadiargyl 80 % WP at 30 g a.i. ha^{-1}; T_3: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_4: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_5: Alachlor 50 % EC at 1000 g a.i. ha^{-1} and early post-emergent (EPoE) application of T_6: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_7: Diuron 80 % WP at 1000 g a.i. ha^{-1}; T_8: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_9: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_{10}: Quizalofop ethyl 5 % EC at 60 g a.i. ha^{-1}; T_{11}: Inter-cultivation at 35 DAS *fb* hand weeding; T_{12}: Hand weeding at 20 and 40 DAS and T_{13}: weedy check.

at 1000 g ha^{-1} (27.6 %). Significantly higher weed index values were observed with oxadiargyl 80 % WP at 30 g ha^{-1} (73.4 %) and pendimethalin 30 % EC applied as EPoE at 750 g and 1000 g ha^{-1} (63.1 % and 67.5 % respectively) compared to pendimethalin 30 % EC at 750 g ha^{-1} as PE (20.5 %). This indicates that, despite achieving relatively good weed control, these treatments were ineffective overall due to their phytotoxic effects on the sesame crop, which negatively impacted yield performance. The Treatment Efficiency Index (TEI) represents the yield advantage achieved through a specific treatment compared to the control, based on the reduction in weed dry matter. TEI is calculated using weed and crop data recorded at harvest. A perusal of the data presented in Table 5 revealed that the herbicidal efficiency index was affected to a considerable extent by different treatments, with TEI values ranging from -3.79 to 8.03. Pendimethalin 30 % EC at 750 g ha^{-1} (8.03) and alachlor 50 % EC at 1000 g ha^{-1} (6.82) as PE application recorded with high positive TEI values demonstrated excellent weed control and minimal crop damage, indicating their suitability for effective weed management. Conversely, treatments with negative TEI values T_1 (-2.22), T_6 (-3.79) and T_7 (-2.58), even though these herbicides are potent against weeds, their current application rate is detrimental to crop health and shows severe crop phytotoxicity, rendering them unsuitable for use.

Hand weeding conducted at 20 DAS and 40 DAS demonstrated the lowest weed persistence index (WPI) of 0.32, alongside the highest treatment efficiency index (TEI) of 30.17 and crop resistance index (CRI) of 23.96, thereby indicating its efficacy in controlling weeds in sesame (Table 5). Among the herbicides evaluated, the application of pendimethalin 30 % EC at 750 g ha^{-1} as PE yielded superior values for TEI (8.03), CRI (7.47), weed management index (WMI) (5.25) and agronomic management index (AMI) (4.25), while also exhibiting a lower WPI of 0.71 compared to other weed control treatments. The indices of weed persistence (WPI) and treatment efficiency (TEI) indicate the resilience of weeds to control measures and the effectiveness of these measures in suppressing weed growth. A lower WPI combined with a higher TEI signifies effective weed management practices. Additionally, a higher crop resistance index reflects an improved ability of the crop to compete with weeds due to the applied weed control strategies. Positive efficiency indices for various weed management treatments have been reported in mustard, cotton and dry-seeded rice (16, 29, 30).

Effect of different weed management treatments on the phytotoxicity of sesame

The phytotoxic effects of herbicides on sesame were evaluated based on visual observation at 15 DAA (Fig. 2). Among the herbicides tested, all early post-emergence herbicides caused sesame injury. The highest crop injury (100 %) at 15 days after application (DAA) was observed from the application of metribuzin 70 % WP at 300 g ha^{-1} as PE and EPoE and diuron 80 % WP at 1000 g ha^{-1} as EPoE. Crop injury consists of leaf chlorosis and leaf necrosis, resulting in the complete death of plants. The lowest crop injury (10 %) was recorded from applying pendimethalin 30 % EC at 1000 g ha^{-1} as PE and its symptoms were gradually recovered by sesame seedlings within a week, while no crop injury was observed from the PE application of pendimethalin 30 % EC at 750 g ha^{-1} and alachlor 50 % EC at 1000 g ha^{-1}. Similarly, pendimethalin 30 % EC at 750 g ha^{-1} & 1000 g ha^{-1} and quizalofop ethyl 5 % EC at 60 g ha^{-1} as EPoE recorded a crop injury of 50 %, the plant showed a patchy necrotic appearance on leaves, leaf discoloration, curling and stunting followed by some plant stand loss that decreased plant population and reduced crop yield. Post-emergence herbicides used for controlling broadleaf weeds in sesame production have been reported to cause crop injury, reduce plant stand, or lower sesame yield (31, 32). Diuron applied at 2 weeks after emergence (WAE) resulted in greater injury (48 % plant injury) compared to application at 4 WAE (23 % plant injury) (32). Metribuzin, oxyfluorfen and their combination (metribuzin + oxyfluorfen) caused the highest levels of sesame phytotoxicity at 7 DAA (33).

Effect of different weed management treatments on the growth of sesame

Different weed control treatments positively influenced the growth and development of sesame compared to the untreated control. Notably, a significant and temporary increase in the LAI was observed with the application of various weed management strategies (Fig. 3A), reaching peak

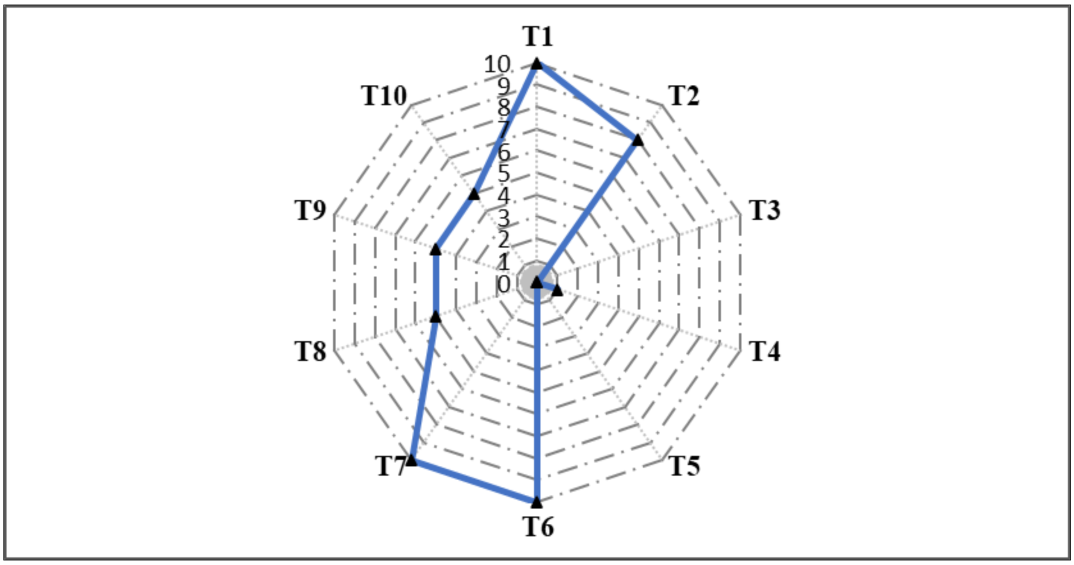

Fig. 2. Phytotoxicity score (1-10) as affected by different weed management treatments in sesame at 15 days after application (pooled data over 2 years).

values at 60 days after sowing (DAS) before subsequently declining. It is important to note that treatments utilising pre-emergent herbicides resulted in a greater leaf area index compared to those employing early post-emergent herbicides. The highest leaf area index values were recorded in treatments that involved manual weeding conducted twice (6.4). Among the herbicides tested, the pre-emergent application of pendimethalin 30 % EC at 750 g ha^{-1} yielded the highest leaf area index (5.4), followed by alachlor 50 % EC at 1000 g ha^{-1}, which recorded a value of 4.2, in contrast to the weedy check, which had a leaf area index of only 1.06. Conversely, treatments T_2, T_8, T_9 and T_{10} recorded lower leaf area indices, primarily due to phytotoxic effects that hindered leaf development and overall crop growth. Additionally, leaf area duration, which serves as an indicator of the duration of photosynthetic activity, displayed a similar trend (Fig. 3B). The enhanced leaf area index and duration, especially in the early stages of growth facilitated by various weed control treatments, likely contributed to increased radiation interception over an extended period, as evidenced by higher dry matter accumulation in these treatments. These findings are consistent with the findings from research conducted in Telangana, India (34).

The higher dry matter accumulation was observed with hand weeding at 20 and 40 DAS (31.49 g plant^{-1}) (Table 6) when compared to the weedy check (9.33 g plant^{-1}). Among different herbicide treatments, pre-emergent application of pendimethalin 30 % EC at 750 g ha^{-1} recorded higher dry matter, significantly on par with that of alachlor 50 % EC at 1000 g ha^{-1} as PE. The data regarding crop growth rate (CGR) is shown in Fig. 3C, which reflects that different weed management practices significantly affected the CGR of sesame. At 30-60 DAS, hand weeding at 20 and 40 DAS (19.22 g cm^{-2} day^{-1}) recorded higher CGR, which is statistically similar to pendimethalin 30 % EC at 750 g ha^{-1} (16.61 g cm^{-2} day^{-1}) and was found to be more effective treatment than weedy check (5.97 g cm^{-2} day^{-1}). A comparable trend in crop growth rates was noted from 60 DAS until harvest. The enhancements observed in these growth parameters, in comparison to the weedy control, indicate the efficacy of various weed management strategies in reducing competition between weeds and crops, thereby facilitating improved crop growth. Enhanced resource acquisition and utilisation may have played a significant role in promoting rapid growth and increased biomass accumulation in sesame plants. The observed improvements in sesame growth characteristics, influenced by effective weed control measures, align with the findings from research conducted in West Bengal, India (35).

Effect of weed management practices on nutrient removal by weeds and nutrient uptake by sesame

Weed management had a significant impact on the removal of major nutrients (NPK) by weeds at harvest (Table 6). Weeds typically grow aggressively, depleting soil nutrients at a faster rate than the associated crop, leading to nutrient deficiencies in crop plants (36). Correlation data clearly indicated that NPK uptake by weeds at harvest had a negative correlation with grain yield and crop dry matter accumulation (Fig. 4). Weed management practices substantially reduced nutrient depletion by weeds. By harvest, nutrient removal by weeds decreased by 25.5 % to 90.2 % for nitrogen (N), 29.2 % to 90.5 % for phosphorus (P) and 25.29 % to 87.83 % for potassium (K) compared to the untreated weedy check. Reduced dry matter accumulation and nutrient content in weeds were observed due to effective weed management, particularly with the PE application of pendimethalin 30 % EC at 750 g ha^{-1}. Significantly higher NPK uptake was recorded in all the weed management practices as compared to the weedy check. The highest NPK uptake (64.65 kg N, 20.46 kg P and 39.55 kg K ha^{-1}) was recorded in two hand weeding at 20 and 40 DAS, which was found at par with pendimethalin 30 % EC at 750 g ha^{-1} and significantly superior to those recorded in the rest of the treatments. Increased productivity and nutrient content in sesame contributed to the higher nutrient uptake, while the lower weed population and dry weight in these treatments played a key role. Nutrient removal by weeds was found to be directly proportional to their biomass and nutrient concentration (37). Weed management significantly reduced nutrient removal by weeds, as previously reported (38). The present study also demonstrated a negative correlation between crop yield and nutrient uptake by weeds (Fig. 4).

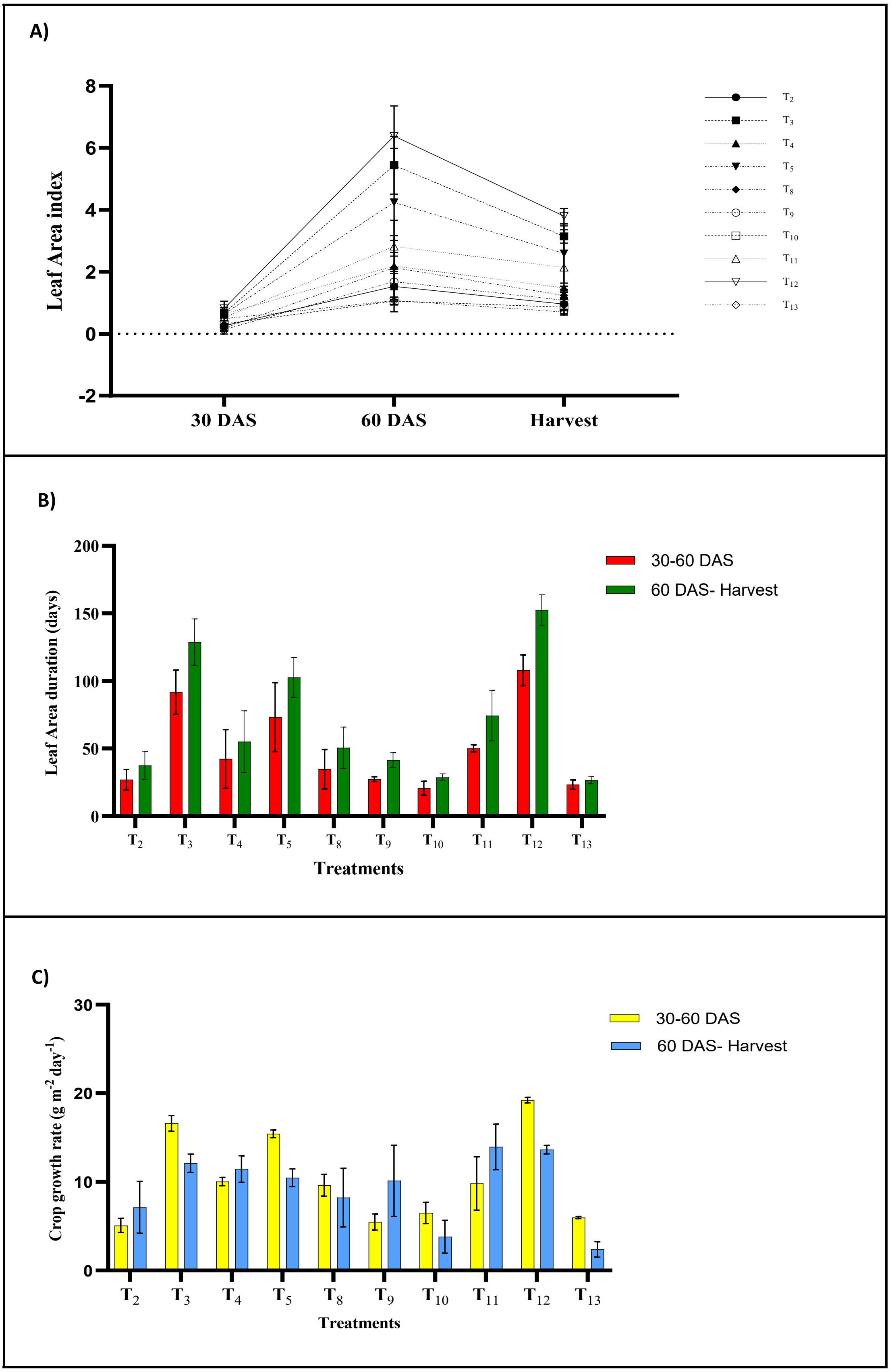

Fig. 3. Influence of different weed management treatments on A) Leaf area index, B) Leaf area duration (days) and C) Crop growth rate (g m^{-2} day^{-1}). The vertical bar represents the standard error of the means. (pooled data over 2 years).

T$_1$: Metribuzin 70 % WP at 300 g ha^{-1} (PE); **T$_2$:** Oxadiargyl 80 % WP at 30 g ha^{-1}; **T$_3$:** Pendimethalin 30 % EC at 750 g ha^{-1} (PE); **T$_4$:** Pendimethalin 30 % EC at 1000 g ha^{-1} (PE); **T$_5$:** alachlor 50 % EC at 1000 g ha^{-1}; **T$_6$:** Metribuzin 70 % WP at 300 g ha^{-1} (EPoE); **T$_7$:** Diuron 80 % WP at 1000 g ha^{-1}; **T$_8$:** Pendimethalin 30 % EC at 750 g ha^{-1} (EPoE); **T$_9$:** Pendimethalin 30 % EC at 1000 g ha^{-1} (EPoE); **T$_{10}$:** Quizalofop ethyl 5 % EC at 60 g ha^{-1}; **T$_{11}$:** Inter-cultivation at 35 DAS *fb* hand weeding; **T$_{12}$:** Hand weeding at 20 and 40 DAS; **T$_{13}$:** Unweeded control.

Weed control has a considerable impact on sesame nutrient uptake (NPK) (Table 6). Weed management improved N uptake by 41 - 288 %, P uptake by 33.6—-234.3 % and K uptake by 44.1 - 298.2 % when compared to the weedy check. The observed increase in major nutrient uptake was attributed to a significant decrease in weed biomass and density. Better weed control created a competition-free environment for crop development. NPK absorption by crops was shown to be closely related to nutrient content and dry matter production (DMP) (Fig. 4). The greater NPK absorption observed in weed management treatments can be attributed to higher DMP and nutrient content. These treatments effectively controlled weeds, likely making more nutrients available to the crop, which in turn promoted a higher nutrient concentration, increased yield and subsequently greater nutrient uptake. A similar trend, where weed management significantly enhanced the uptake of major nutrients, was observed in soybean (39).

Among all treatments, the weedy check exhibited the highest nutrient removal by weeds due to unchecked weed growth. This uncontrolled proliferation depleted soil nutrients and moisture, negatively impacting dry matter production (DMP) in sesame. The increased dry matter accumulation in weeds was the primary factor contributing to the higher NPK removal observed in the weedy check (Table 6).

Effect of different weed management treatments on yield attributes and yield of sesame

The number of capsules per plant, seed and stalk yield (kg ha^{-1}) of sesame as influenced by various weed management treatments are presented in Table 7. The weed-free treatment had the highest number of capsules per plant, sesame seed yield and stalk yield due to larger plants and greater yield attributes, whereas the weedy check had the lowest values. In *kharif* sesame, uncontrolled weeds lowered the number of capsules per plant, seed and stover yields by 84.2, 81 and 69.7 %, respectively, when compared to weed-free treatment (12.61, 616.8 and 2801 kg ha^{-1}). Although hand weeding is effective and environmentally friendly, it is labour-intensive and time-consuming. Therefore, the use of herbicides is essential, as they offer a quicker and more

Table 6. Effect of weed management practices on nutrient removal by weeds and nutrient uptake by sesame at harvest (pooled data over 2 years)

Treatments	Nutrient removal by weeds (kg ha^{-1})			Nutrient uptake by crop (kg ha^{-1})		
	N	P	K	N	P	K
T_1	24.06^{e}	3.80^{e}	18.65^{e}	-	-	-
T_2	39.13^{c}	7.46^{c}	30.71^{c}	25.12^{f}	8.39^{e}	15.03^{e}
T_3	20.62^{f}	3.03^{f}	16.04^{f}	54.33^{b}	16.70^{b}	32.02^{b}
T_4	27.43^{d}	4.52^{d}	21.37^{d}	36.90^{d}	12.09^{cd}	22.38^{c}
T_5	21.56^{f}	3.21^{f}	16.74^{f}	53.53^{bc}	16.50^{b}	31.30^{b}
T_6	12.73^{g}	1.60^{g}	10.27^{g}	-	-	-
T_7	20.85^{f}	3.12^{f}	16.09^{f}	-	-	-
T_8	19.43^{f}	2.82^{f}	15.22^{f}	36.54^{d}	12.39^{c}	21.51^{c}
T_9	25.02^{e}	3.88^{e}	19.40^{e}	33.07^{e}	11.02^{d}	19.19^{d}
T_{10}	42.07^{b}	8.29^{b}	33.16^{b}	23.49^{f}	8.18^{e}	14.31^{e}
T_{11}	14.18^{g}	1.81^{g}	11.35^{g}	50.54^{c}	16.48^{b}	30.56^{b}
T_{12}	5.54^{h}	1.11^{h}	5.40^{h}	64.65^{a}	20.46^{a}	39.55^{a}
T_{13}	56.49^{a}	11.71^{a}	44.39^{a}	16.66^{g}	6.12^{f}	9.93^{f}
S.Em. ±	**0.72**	**0.14**	**0.60**	**1.07**	**0.43**	**0.70**
C.D. at 5 %	**2.12**	**0.41**	**1.75**	**3.17**	**1.27**	**2.07**

'-' indicates data not available due to complete crop phytotoxicity; Treatments T1, T6 and T7 are not included in the statistical analysis for nutrient uptake by crop; Common letters are non-significant according to Duncan's multiple range test where $p < 0.05$; T_1: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_2: Oxadiargyl 80 % WP at 30 g a.i. ha^{-1}; T_3: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_4: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_5: Alachlor 50 % EC at 1000 g a.i. ha^{-1} and early post-emergent (EPoE) application of T_6: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_7: Diuron 80 % WP at 1000 g a.i. ha^{-1}; T_8: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_9: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_{10}: Quizalofop ethyl 5 % EC at 60 g a.i. ha^{-1}; T_{11}: Inter-cultivation at 35 DAS *fb* hand weeding; T_{12}: Hand weeding at 20 and 40 DAS and T_{13}: weedy check.

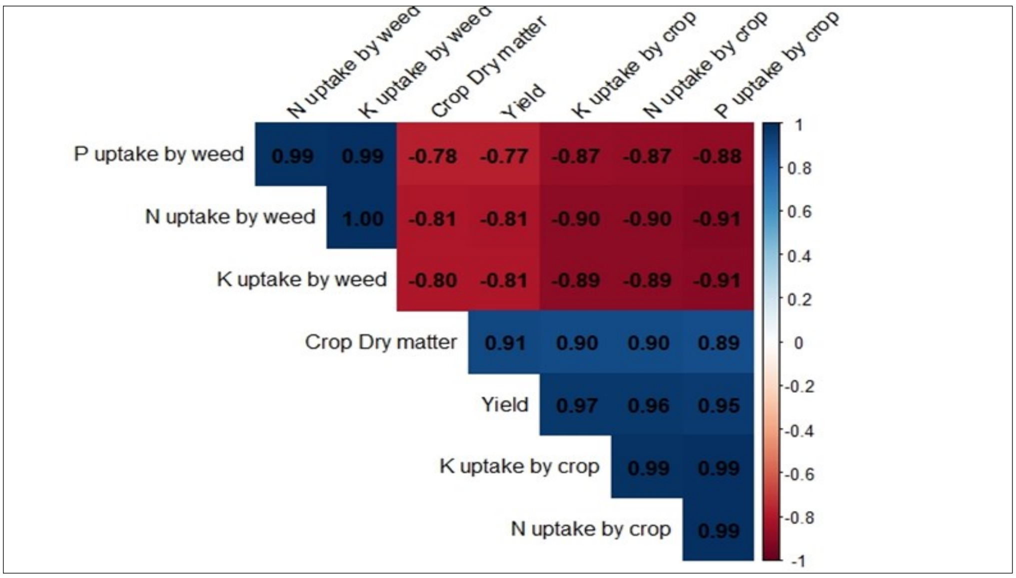

Fig. 4. Correlation between nutrient uptake by crop and weed, crop dry matter and grain yield.

Table 7. Effect of weed management practices on yield attributes, yield and economics of sesame (pooled data over 2 years)

Treatments	Dry matter (g plant^{-1})	Number of capsules per plant	Seed yield (kg ha^{-1})	Stalk yield (kg ha^{-1})	Cost of cultivation (₹ ha^{-1})	Net returns (₹ ha^{-1})	BC ratio
T_1	-	-	-	-	27859	-	-
T_2	11.91^{ef}	17.96^{e}	164.2^{gh}	1124^{f}	26781	745^{f}	1.03^{e}
T_3	27.58^{ab}	58.13^{b}	489.7^{b}	2459^{b}	28044	54068^{b}	2.92^{ab}
T_4	21.22^{cd}	41.79^{c}	331.3^{e}	1891^{d}	28608	26900^{d}	1.94^{c}
T_5	25.02^{bc}	56.62^{b}	446.1^{c}	2320^{bc}	27282	47565^{b}	2.74^{b}
T_6	-	-	-	-	27859	-	-
T_7	-	-	-	-	27571	-	-
T_8	16.83^{de}	33.75^{d}	227.7^{f}	1533^{e}	28044	10125^{e}	1.36^{d}
T_9	15.03^{ef}	32.32^{d}	200.5^{fg}	1379^{e}	28608	5014^{ef}	1.17^{de}
T_{10}	10.43^{f}	16.46^{e}	123.9^{h}	880^{g}	28982	-8244^{g}	0.72^{f}
T_{11}	23.04^{bc}	52.67^{b}	390.1^{d}	2154^{c}	31632	33735^{c}	2.07^{c}
T_{12}	31.49^{a}	80.03^{a}	616.8^{a}	2801^{a}	34322	68903^{a}	3.01^{a}
T_{13}	9.33^{f}	12.61^{e}	117.5^{h}	833^{f}	25972	-6308^{g}	0.76^{f}
S.Em. ±	**1.90**	**2.66**	**13.70**	**74.35**		**2287**	**0.08**
C.D. at 5 %	**5.65**	**7.91**	**40.70**	**220.92**		**6796**	**0.22**

'-' indicates data not available due to complete crop phytotoxicity; Treatments T1, T6 and T7 are not included in the statistical analysis for nutrient uptake by crop; Common letters are non-significant according to Duncan's multiple range test where $p < 0.05$; T_1: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_2: Oxadiargyl 80 % WP at 30 g a.i. ha^{-1}; T_3: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_4: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_5: Alachlor 50 % EC at 1000 g a.i. ha^{-1} and early post-emergent (EPoE) application of T_6: Metribuzin 70 % WP at 300 g a.i. ha^{-1}; T_7: Diuron 80 % WP at 1000 g a.i. ha^{-1}; T_8: Pendimethalin 30 % EC at 750 g a.i. ha^{-1}; T_9: Pendimethalin 30 % EC at 1000 g a.i. ha^{-1}, T_{10}: Quizalofop ethyl 5 % EC at 60 g a.i. ha^{-1}; T_{11}: Inter-cultivation at 35 DAS *fb* hand weeding; T_{12}: Hand weeding at 20 and 40 DAS and T_{13}: weedy check.

selective approach to weed control. Pendimethalin 30 % EC at 750 g ha^{-1} as PE application reduced the gap in seed and stalk yield between weedy check and weed-free treatment by 74.6 % and 79.3 % respectively. This could be due to low weed density and competition throughout the crop growth period, which had a positive effect on photosynthesis rate and photosynthate accumulation, followed by efficient partitioning of accumulated photosynthates to the sink, which contributed to the favourable development of yield indices and, ultimately, grain yield (40, 41).

Compared to pendimethalin 30 % EC at 750 g ha^{-1} as PE (489.7 kg ha^{-1}), pendimethalin as EPoE at 750 g and 1000 g ha^{-1} decreased sesame seed yields by 53.5 % and 59.1 %, respectively. The lower yield in plots treated with pendimethalin and quizalofop ethyl can be partly attributed to the phytotoxicity of these herbicides, their reduced effectiveness in controlling weeds and the resulting increase in crop-weed competition. An increase in weed density intensifies weed-crop competition, leading to a significant reduction in crop yield (42). Weed infestation in sesame has been reported to cause yield losses ranging from 20.5 % to 81.0 %. Stalk yields were reduced to about the same extent as seed yields. Because of taller plants and superior yield characteristics, the weed-free treatment produced the highest seed and stalk yields, whereas the weedy check produced the lowest. Grain yields in the other herbicidal treatments were intermediate, reflecting the influence of yield attributes when compared to the weed-free and weedy check treatments. This was in accordance with the findings of different workers who reported that the application of herbicides increased sesame yield and yield components (43–45).

Effect of weed management practices on the economics of sesame

The weed-free treatment costing 8350 increased the cost of sesame crop output by 32.2 % over the weedy check (₹ 25972) and resulted in a significantly greater net revenue (₹ 68903) compared to other weed-management treatments (Table 7). Application of pendimethalin 30 % EC at 750 g ha^{-1} as PE treatment incurred only 24.8 % of the cost of manual weed-free treatment yet resulted in 80.3 % higher net returns compared to weed-check treatment. In terms of benefit: cost (B:C) ratio, pendimethalin 30 % EC at 750 g ha^{-1} as PE (2.92) was comparable to weed-free treatment (3.01). The higher B:C ratio of pendimethalin 30 % EC at 750 g ha^{-1} was attributed to an 18.3 % cheaper production cost than weed-free treatment. A higher benefit-cost ratio clearly indicates the economic viability of the experiment, making it a convincing factor for farmers to adopt the recommended intervention. Over pendimethalin 30 % EC at 750 g ha^{-1} (PE), pendimethalin 30 % EC (750 and 1000 g/ha) as EPoE resulted in net revenue losses of 81.3 and 90.7 % respectively. A similar result was reported in sesame by different workers (27, 46).

Correlation and regression

Regression analyses were performed using pooled data to assess the relationship between seed yield (g m^{-2}) and crop dry matter (g m^{-2}) as dependent variables. The results revealed a negative correlation between sesame seed yield and crop dry matter with weed dry weight, leading to a 57 % and 58 % reduction in yield and crop dry matter respectively (Fig. 5). Specifically, sesame yield declined by approximately 0.26 g m^{-2} (equivalent to 2.58 kg ha^{-1}) for each unit increase in weed dry weight (g m^{-2}). Additionally, sesame leaf area index, leaf area duration and dry matter production showed a positive correlation with grain yield, with regression analyses explaining over 82 % of the yield variation attributed to these growth parameters (Fig. 5). These results are consistent with previous studies conducted in Bangladesh and India, which similarly reported a negative correlation between grain yield and weed biomass at various stages of rice growth (47, 48).

The correlation data between nutrient uptake by weeds and crops, crop dry matter and yield shows a strong negative correlation between nutrient uptake by weeds (P, N and K) and crop dry matter and yield, with values ranging from -0.77 to -0.91 (Fig. 4). This indicates that higher nutrient uptake by weeds significantly reduces crop growth and

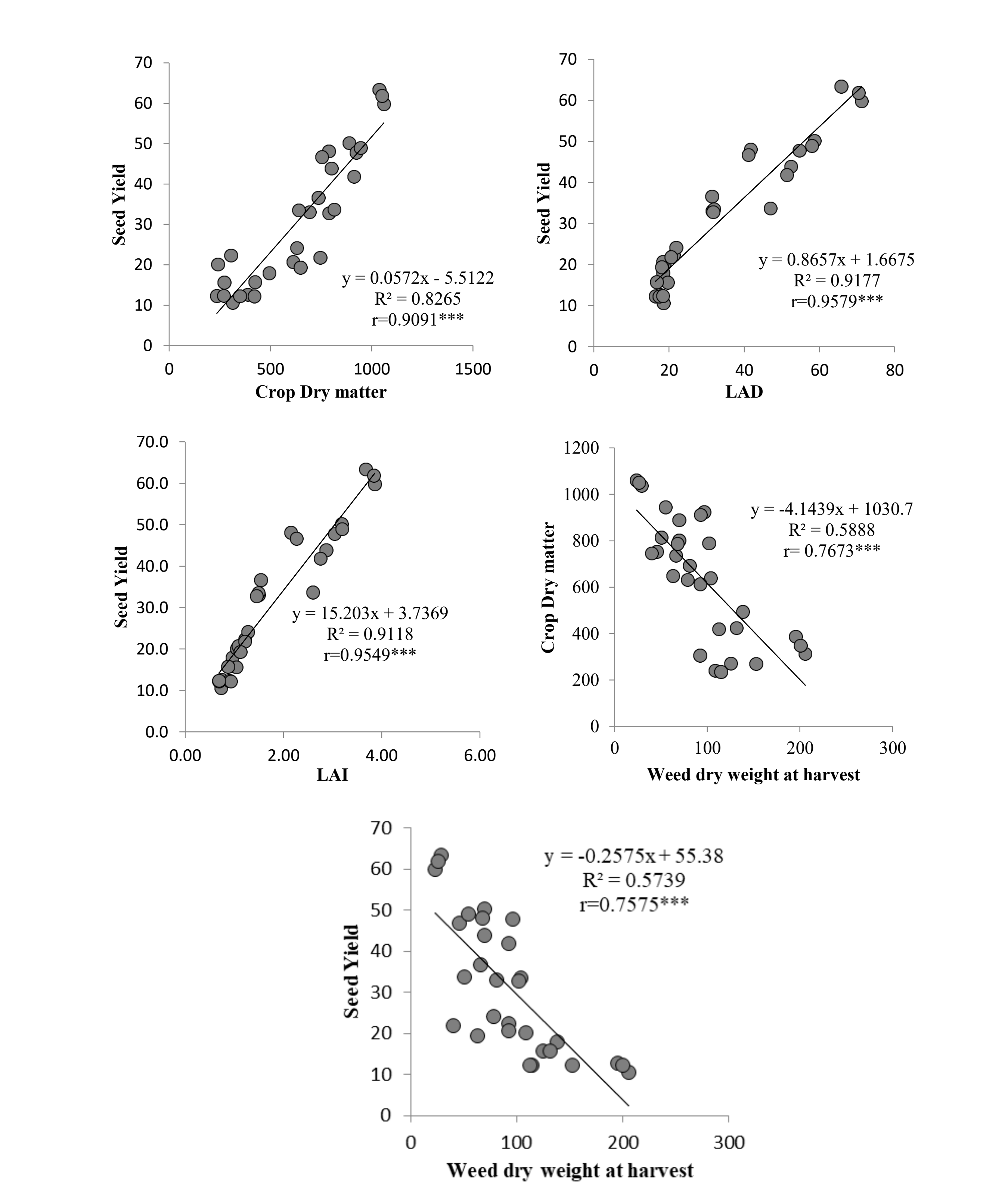

Fig. 5. Relationship of seed yield (g m^{-2}) with crop dry matter (g m^{-2}), LAD (days), LAI and total weed dry weight at harvest (g m^{-2}) in sesame as affected by different weed management practices. R^2 = coefficient of determination; r = correlation coefficient. *$p \leq 0.05$, **$p \leq 0.005$, ***$p \leq 0.001$, (n = 30).

productivity. Conversely, there is a strong positive correlation (0.89 - 0.99) between crop dry matter, yield and nutrient uptake by crops, suggesting that weeds absorb these nutrients at a high rate, they deprive the crops of the necessary resources required for their growth, leading to reduced biomass accumulation, lower dry matter content and ultimately diminished yield. Reduced nutrient availability can lead to stunted growth, poor root development and lower photosynthetic efficiency in crops.

Conclusion

The research findings clearly demonstrate that effective weed management is crucial for optimising the growth and yield of sesame. Among the various treatments evaluated, the pre-emergent application of pendimethalin 30 % EC at 750 g ha^{-1} was particularly effective, significantly reducing weed density and dry weight while maintaining crop health. Hand weeding at 20 and 40 DAS also proved highly effective, but was less practical due to increased labour costs. Although some herbicides like metribuzin and diuron showed high weed control efficiency, their severe phytotoxicity on the sesame crop renders them unsuitable for use. The study highlights the importance of selecting herbicides that balance weed control with minimal crop injury, as evidenced by the superior performance of pendimethalin in terms of yield, weed control efficiency and economic returns. The correlation between reduced nutrient uptake by weeds and increased crop yield further underscores the benefits of effective weed management strategies. These findings suggest that integrating pre-emergent herbicides with proper application timing can enhance sesame productivity and sustainability.

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Authors' contributions

DG carried out the experiment, analysis and manuscript writing. GKN carried out supervision and software analysis. PN carried out the manuscript editing. MK, KR and SJK carried out the analysis and manuscript editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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