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Effect of weed management on growth, yield and economics of dill (*Anethum graveolens* L.) in typic haplustept soils

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Weed management is a critical factor influencing returns yield and economic returns of dill (*Anethum graveolens* L.). A field experiment was conducted during the *rabi* seasons of 2020–2021 and 2021–2022 at MPUA&T, Udaipur, Rajasthan, to evaluate the efficacy of various weed control strategies in dill cultivation. The study, laid out in a randomized block design with three replications, comprised thirteen weed control treatments, including pre and post emergence herbicides and integrated approaches. The application of oxadiargyl at 75 g/ha as a pre-emergence herbicide, followed by hand weeding at 40 days after sowing (DAS), resulted in the highest weed control efficiency (96.42% at 60 DAS) and significantly reduced weed density and biomass. This treatment improved growth attributes such as plant height, dry matter accumulation, and branches per plant, leading to a 61.58% increase in seed yield (7.66 q/ha) compared to the weedy check (4.74 q/ha). Economic analysis revealed that this integrated approach provided the highest net return (USD 770.59/ha) and benefit-cost ratio (1.93), making it the most effective and profitable weed management strategy for dill cultivation.

Keywords Dill, Oxadiargyl, Seed spices, Weeds, Weed management

Abbreviations

HW	Hand weeding
IC	Inter cultivation
DAS	Days after sowing
N	North
°C	Degree Celsius
Q	Quintal
M	Metres
USD	US dollars
WCE	Weed control efficiency
-1	Per
&	And
PE	Pre-emergence
PoE	Post-emergence
B-C	Benefit cost ratio
E	East
DAP	Di ammonium phosphate
Ha	Hectares
et al.	And others
Fb	Followed by
WI	Weed index
G	grams

Dill (*Anethum graveolens* L.) belongs to *the Apiaceae* family. During the 2019–2020 period in India, dill was grown on approximately 32.79 thousand hectares, yielding around 34.56 thousand tonnes of seeds, with average

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productivity of 1054 kg per hectare[1]. It is a versatile crop widely appreciated for its seeds and leaves, commonly used to enhance the flavour of various dishes, including sauces, vinegar, pastries and soups[2]. The seeds are known for their medicinal benefits, acting as stimulants, diuretics and carminatives[3]. The primary active components of dill seeds' essential oil are carvone and limonene[4], which contribute to these properties. In traditional medicine, dill is recognised for its diuretic, antispasmodic and galactagogue effects[5].

Additionally, dill seeds are high in vitamins C, A, B_3, B_2, and B_9 and minerals such as potassium, copper, calcium, manganese, iron & magnesium[6]. Dill is resilient to pests and diseases, ensuring stable yields[7]. It tolerates moisture stress across growth stages, thriving in diverse climates, including water-limited regions and heavy soils like black soils[8]. However, dill cultivation also faces numerous challenges, with weed interference being a significant constraint.

Weed infestation is a major constraint in dill cultivation, leading to significant yield losses, estimated at 50–60% [9], depending upon the weed flora. The crop is predominantly infested with a diverse spectrum of weed species, including *Chenopodium album*, *Melilotus indica*, *Fumaria parviflora*, *Convolvulus arvensis*, *Malva parviflora*, *Chenopodium murale* and *Phalaris minor*[10–13]. These weeds compete for critical growth resources such as nutrients, moisture and light adversely affecting crop growth, yield and quality[14]. The problem is further exacerbated by the delayed germination of dill, making it highly susceptible to early-season weed competition[15]. Given these challenges, effective weed management strategies are imperative to enhance productivity and ensure sustainable dill cultivation. Weed management in dill is crucial for minimizing yield losses and ensuring optimal crop growth. Various approaches including manual weeding and chemical interventions, are employed, each with distinct advantages and limitations[16]. While hand-weeding is a common practice, especially on small farms, its labour intensive nature and high costs make it less viable in regions with limited labour availability. In such cases, herbicides serve as an efficient alternative, offering a three-to-four-fold economic return compared to traditional methods[17]. Pre-emergence herbicides such as pendimethalin and oxadiargyl have demonstrated effectiveness in suppressing weeds, but their residual activity necessitates careful integration with post-emergence treatments for season-long control[18]. Each year, the variability in weed seedling emergence further underscores the need for flexible weed management strategies. Herbicides, due to their selectivity, cost-effectiveness and ease of application, provide a reliable solution for weed control in diverse agronomic conditions[19,20]. Their application has been shown to enhance crop productivity significantly, as observed in fennel, where yield improvements ranged from 43.2 to 86.9% following effective weed suppression[21]. A strategic integration of manual and chemical weed control measures is essential for sustaining weed-free conditions and optimizing dill production. Adopting a balanced weed management approach can improve resource utilization, reduce competition, and enhance overall crop performance.

A significant knowledge gap exists in the literature regarding adequate doses of herbicides, time of application and economics for efficient weed management strategies on dill yield and quality across different agricultural contexts. Effective weed suppression through a combination of manual and chemical control methods enhances root development and seed formation, leading to improved nutrient uptake. This, in turn, may contribute to higher oil content in dill [22] . This gap presents an opportunity to investigate and optimize weed control methods to enhance the productivity of dill cultivation. While some weed management strategies have been explored, comparative research on their effectiveness in dill is limited. Most studies have emphasized the chemical properties of dill's essential oil, rather than improved production practices, highlighting the need for more targeted research on the effectiveness and economic viability of various weed control methods. This study addresses these gaps by systematically evaluating the impact of diverse weed management practices on dill seed yield and quality. By comparing manual and chemical methods, this research aims to provide actionable insights for both farmers and practitioners. This study assesses integrated weed management strategies for dill, considering both agronomic and economic dimensions, which contribute to the development of sustainable agricultural practices with the potential to improve productivity and quality within the spice industry.

Materials and methods
Experimental site
The experiment was carried out at the instructional farm of Rajasthan College of Agriculture, MPUA&T, Udaipur, Rajasthan, during the *rabi* seasons of 2020–2021 and 2021–2022. The research site (Fig. 1), located at an altitude of 581.13 m above sea level (24°35'N latitude, 74°42'E longitude), falls within agro-climatic zone IVa of Rajasthan (Sub-Humid Southern Plain and Aravalli Hills). The soil was clay loam, non-saline and slightly alkaline (pH 8.05) with medium nitrogen (318.64 kg ha^{-1}), organic carbon (0.56%), phosphorus (25.11 kg ha^{-1}) and high potassium (465.55 kg ha^{-1}). Udaipur experiences a typical winter and moderate summer climate with an average annual rainfall of 637 mm mostly during June to September. The climatic conditions displayed variability between the two experimental periods on an interannual scale (Fig. 2).

Cropping history
During the study period (2020–21 and 2021–22), a soybean–dill rotation was practiced at the experimental site, with soybeans cultivated in the *Kharif* season followed by dill in the *Rabi* season. Soybean cultivation enriches soil fertility by fixing atmospheric nitrogen, which enhances nutrient availability and the availability of nutrients for the succeeding dill crop. Moreover, its crop residue and canopy coverage can inhibit weed emergence, thereby minimizing weed competition in dill during the *Rabi* season[26].

Variety details
European dill variety 'NRCSS-AD-1 (Ajmer sowa-1)'is characterized by an average plant height of 134 cm and reaches maturity in approximately 142 days. Under irrigated conditions, it produces an average seed yield of 14.7 q ha^{-1} and was sown in rows spaced 30 cm apart at the rate of 3 kg ha^{-1} with the standard package of practices.
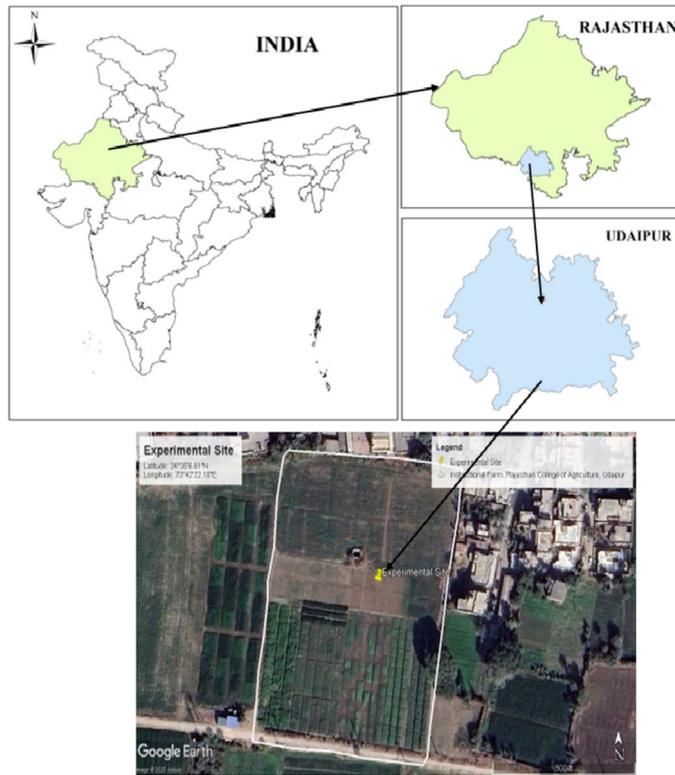
Fig. 1. Geographical location of the experimental site at the instructional farm, Rajasthan College of Agriculture (RCA), MPUAT, Udaipur, Rajasthan, India. The satellite imagery used in this figure was developed using the freely available software QGIS 3.22.3[24] (https://qgis.org). The satellite imagery was taken from the freely available source Google Earth[25] (https://earth.google.com).
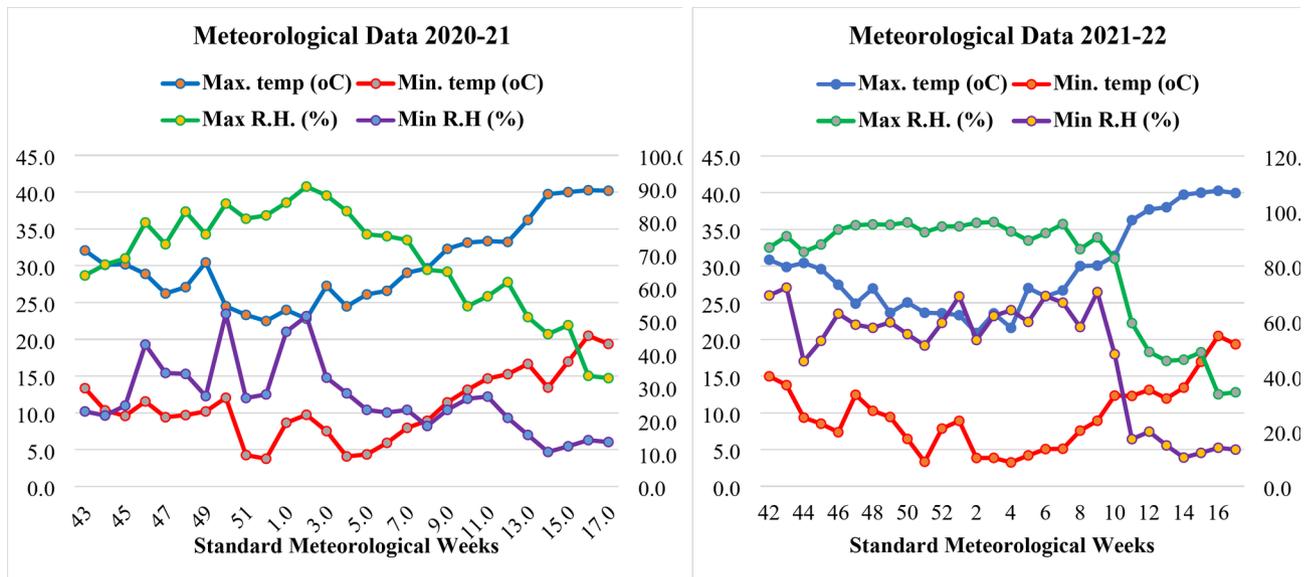

Fig. 2. Meteorological data for the experiment site during the experimental periods.

Irrigation and fertilization

Effective irrigation is necessary for dill to thrive and yield at its best. Depending on the crops' needs, three to four irrigations were applied as per requirement. Three irrigations were provided in 2020–21, while two irrigations were provided in 2021–22 with the additional moisture requirements fulfilled by rainfall. Excessive irrigation

Annotations	Treatment	Dose (g ha^{-1})	Time of application
T$_1$	Pendimethalin	1000	PE
T$_2$	Pendimethalin *fb* HW at 40 DAS	750	PE
T$_3$	Pendimethalin *fb* quizalofop ethyl	750 *fb* 40	PE *fb* PoE (3–4 leaf stage)
T$_4$	Oxadiargyl	100	PE
T$_5$	Oxadiargyl *fb* HW at 40 DAS	75	PE
T$_6$	Oxadiargyl *fb* quizalofop ethyl	75 *fb* 40	PE *fb* PoE (3–4 leaf stage)
T$_7$	Oxadiargyl	50	PoE (3–4 leaf stage)
T$_8$	Oxyfluorfen	100	PE
T$_9$	Oxyfluorfen *fb* HW at 40 DAS	75	PE
T$_{10}$	Oxyfluorfen *fb* quizalofop ethyl	75 *fb* 40	PE *fb* PoE (3–4 leaf stage)
T$_{11}$	IC *fb* HW at 20 & 40 DAS		
T$_{12}$	Oxadiargyl + propaquizafop (TM)	50 + 50	PoE (3–4 leaf stage)
T$_{13}$	Weedy check		

Table 1. Treatment details. A weedy check denotes a control plot in which no weed management strategies are implemented, permitting the unrestricted growth of weeds during the crop's growth phase. IC represents inter cultivation and HW represents hand weeding.

S. No.	Common name	Chemical name	Chemical group	Mechanism of action	References
1.	Pendimethalin	N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine	Dinitroanilines	Microtubule assembly inhibitors	(Kalyabina et al. 2021)
2.	Quizalofop ethyl	Ethyl 2-[4-{(6-Chloro-2-quinoxalinyl) oxy} phenoxy] propanoate	Phenoxy propionates	acetyl–CoA carboxylase (ACCase) inhibitors	(Rustom et al. 2019)
3.	Oxyfluorfen	2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)-benzene	Di phenyl ether	Protoporphyrinogen oxidase (PPO inhibitors)	(Aliverdi et al. 2020)
4.	Oxadiargyl	5-tert-butyl-3-{2,4-dichloro-5-(propynyl)phenyl}-1,3,5-oxadizole-2-(3 H)-one	oxadiazoles	Protoporphyrinogen oxidase (PPO inhibitors)	(Ahmed and Chauhan 2015)
5.	Propaquizafop	2-isopropylideneaminooxyethyl(R)-2-[4-{(6-chloroquinoxalin-2 yloxyl)}phenoxy] propionate	Phenoxy propionates	Acetyl coenzyme-A carboxylase (ACCase) inhibitors	(Jursík et al. 2021)

Table 2. Details of herbicides used.

can foster conditions conducive to weed multiplication and may result in herbicide leaching, diminishing their efficacy in weed management.

Fertilizers were applied at recommended doses of 90 kg N ha^{-1}, 40 kg P$_2$O$_5$ ha^{-1} and 20 kg K$_2$O ha^{-1} through di ammonium phosphate (DAP) and urea. DAP was applied entirely as a basal dose while urea was applied in splits 1/3rd as a basal dose and the remaining 2/3rd as equal splits during crop vegetative growth at an interval of 2–3 weeks.

Treatment details

The study comprised thirteen treatments (Table 1) laid in a three replication randomized block design[27]. Herbicidal treatments were applied using a knapsack sprayer with a flat fan nozzle as per treatment using 500 L of water[28]. Pre-emergence herbicides were applied 1–3 days after sowing (DAS), post emergence herbicides were applied at 20 DAS[29]. Details of the different herbicides used in the study are listed in Table 2.

Observations recorded

Weed density and dry matter
Data on weed density was recorded at 60 DAS with quadrants of 0.5 m × 0.5 m plot^{-1}. All weeds within the quadrant were cut close to the ground and collected by their category in paper bags. These weed samples were then dried in an oven at 65 °C for 8 h and then the dry matter was recorded[30].

Weed control efficiency and weed index
Weed control efficiency (WCE %) and weed index (WI) were calculated by considering weed dry matter and seed yield using the following formula suggested by[31].

$$WCE = \frac{DMC - DMT}{DMC} \times 100 \tag{1}$$

$$WI = \frac{X - Y}{X} \times 100 \tag{2}$$

where DMC is the dry weight of weeds in the control plot (T_{12} Weedy check); DMT is the dry matter weight of weeds in the treated plot; X is the yield from best-performing treatment (T_5 Oxadiargyl *fb* HW at 40 DAS); Y is the yield from the treated plot.

Growth, yield and yield attributes
Growth and yield attributes were assessed from five randomly selected plants per treatment, and yield was determined on a per-hectare basis at harvest maturity. Following threshing, the dill seed and straw yield from each treatment plot was quantified, with weights expressed in quintals per hectare (q ha^{-1}).

Economic assessment
The total cost of cultivation was determined by considering all cultivation costs, from preparatory tillage to harvesting, accounting for inputs such as seeds, fertilizers and labour. Then, net return (USD ha^{-1}) and b-c ratio were calculated using the following formulae[32]:

$$\text{Net Return} = \text{Gross return} - \text{cost of cultivation} \qquad (3)$$

$$\text{B} - \text{C ratio} = \frac{\text{Net return}}{\text{Cost of cultivation}} \qquad (4)$$

Statistical analysis
The data obtained were analysed using analysis of variance (ANOVA), followed by the F-test. Mean comparisons were performed using the Tukey HSD test at a 5% significance level. All statistical analyses were conducted with R Studio software, version 1.3.1093 [33]. The data of weed density and dry matter were subjected to square root transformation $(X + 0.5)$ to normalize their distribution[34] where "X" is the original data. The correlation between weed index and seed was drawn using the standard procedure[35]. The statistical analysis (Table 3) reveals a significant impact of the applied weed management treatments on multiple parameters. Each parameter is analyzed through the sum of squares (SS), degrees of freedom (DF), mean square (MS), F value, and P value, with all P values being < 0.001 indicating significant treatment effects. The high F values for total weed density and dry matter accumulation demonstrate strong impacts from the treatments. Parameters like plant height and branches per plant also show notable variations. Economic indicators such as net return and benefit-cost ratio also reflect substantial improvements. These results confirm that the treatments significantly influenced crop outcomes and economic returns.

Results
Effect on weed density, weed dry matter and weed control efficiency
The experimental plots were infested predominantly with broadleaved weeds rather than grassy. With the application of different treatments, a reduction in weed density and dry matter was observed compared to weedy check at 60 days after sowing (DAS). Oxadiargyl with its four different combinations, namely sole oxadiargyl 100 g ha^{-1} PE, oxdiargyl 75 g ha^{-1} fb HW at 40DAS, oxadiargyl 75 g ha^{-1} *fb* quizalofop ethyl 40 g ha^{-1} PoE and oxadiargyl 50 g ha^{-1} PoE managed to reduce weed density and dry matter. Out of them, the treatment emergence application of oxadiargyl 75 g ha^{-1} followed by hand weeding at 40 DAS exhibited the lowest weed density and dry matter for monocot (1.08 m^{-2}, 0.91 g m^{-2}), dicot (5.49 m^{-2}, 4.45 g m^{-2}) and total weeds (6.57 m^{-2}, 5.35 g m^{-2}) which achieved a 20.65% reduction in weed infestation over inter cultivation (IC) with HW at 20 and 40 DAS.

Notably, oxadiargyl 75 g ha^{-1} PE *fb* HW 40 DAS achieved the highest weed control efficiency (96.42%) and the lowest weed index indicating superior weed management (Table 4). In addition, the application of pendimethalin either independently or in conjunction with manual weeding and quizalofop ethyl demonstrated superior efficacy compared to alternative treatments. Among chemicals oxadiargyl 50 g ha^{-1} + propaquizafop 50 g ha^{-1} PoE was outperformed by other treatments except weedy check. As a result of the decreased dry weight

Source	SS	DF	MS	F value	*P* Value	Mean
Total Weed density	283.63	12	23.64	12810.02	< 0.005	4.78
Total Weed Dry matter	228.77	12	19.06	10467.99	< 0.005	4.33
Plant height	3088.4	12	257.36	6.58	< 0.005	161.77
Dry matter accumulation	228.77	12	19.06	10467.99	< 0.005	133.20
Branches per plant	35.48	12	2.95	14.814	< 0.005	5.85
Umbels per Plant	354.5	12	29.54	35.617	< 0.005	10.34
Umbellets per Plant	146.9	12	12.24	21.553	< 0.005	16.50
Seed yield	127.6	12	10.63	30.18	< 0.005	9.14
Stover yield	354.5	12	29.54	35.617	< 0.005	17.53
Net return	1,124,803	12	93,734	32.490	< 0.005	864.40
B-C ratio	5.5	12	0.46	20.359	< 0.005	1.40

Table 3. Analysis of variance and statistical indicators for various parameters for weed management in dill.

Treatment	Weed density (No m^{-2})			Weed dry matter (g m^{-2})			Weed control efficiency (%)	Weed index (%)
	Grassy weeds	Broadleaved weeds	Total weeds	Grassy	Broadleaved weeds	Total weeds		
T_1	1.85^{ef} (2.97)	3.40^h (11.03)	3.81^g (14.00)	1.73^d (2.49)	3.07^h (8.94)	3.45^g (11.43)	92.64^{abc}	24.82^{bcd}
T_2	1.75^f (2.58)	3.17^i (9.55)	3.55^h (12.13)	1.64^d (2.20)	2.87^i (7.76)	3.23^h (9.96)	93.56^{abc}	22.88^{cd}
T_3	2.21^{bc} (4.41)	4.53^d (20.02)	4.99^d (24.42)	2.07^c (3.77)	4.09^d (16.21)	4.52^d (19.98)	86.83^c	29.06^{bc}
T_4	1.40^g (1.46)	2.89^j (7.84)	3.13^j (9.30)	1.32^e (1.25)	2.61^j (6.34)	2.84^j (7.58)	94.94^{abc}	16.66^{cde}
T_5	1.24^g (1.08)	2.45^l (5.49)	2.66^l (6.57)	1.18^f (0.91)	2.22^l (4.45)	2.42^l (5.35)	96.42^a	0.00^e
T_6	2.19^{bcd} (4.30)	4.33^d (18.27)	4.80^e (22.57)	2.00^c (3.51)	3.92^e (14.86)	4.34^e (18.37)	87.90^{abc}	23.51^{cd}
T_7	1.39^g (1.44)	3.11^i (9.19)	3.34^i (10.63)	1.32^{ef} (1.23)	2.81^i (7.38)	3.02^i (8.62)	94.15^{abc}	23.73^{cd}
T_8	2.14^{cde} (4.12)	3.96^f (15.20)	4.45^f (19.32)	1.98^c (3.44)	3.58^f (12.35)	4.04^f (15.79)	89.77^c	31.27^{bc}
T_9	1.90^{def} (3.13)	3.52^g (11.87)	3.94^g (15.00)	1.72^d (2.47)	3.19^g (9.68)	3.56^g (12.15)	92.06^{bc}	26.48^{bc}
T_{10}	2.26^{bc} (4.63)	4.86^c (23.11)	5.31^c (27.74)	2.09^c (3.88)	4.38^c (18.71)	4.81^c (22.59)	84.95^{bc}	30.09^{bc}
T_{11}	1.33^g (1.27)	2.74^k (7.01)	2.96^k (8.28)	1.25^{ef} (1.06)	2.48^k (5.64)	2.68^k (6.70)	95.49^{ab}	7.94^{de}
T_{12}	2.49^b (5.70)	5.14^b (25.90)	5.67^b (31.60)	2.32^b (4.87)	4.64^b (21.05)	5.14^b (25.92)	82.90^c	41.16^b
T_{13}	5.41^a (28.73)	12.48^a (155.34)	13.59^a (184.08)	4.93^a (23.79)	11.21^a (125.27)	12.23^a (149.05)	0.00^d	61.74^a

Table 4. Effect of weed management practices on weed density, dry matter, weed control efficiency at 60 DAS and weed index (mean of 2 years). Means with the same letter are not significantly different ($P \leq 0.05$) by Tukey's HSD test, while different letters indicate significant differences. The Weed Index was calculated taking T5 (Oxadiargyl *fb* HW at 40 DAS) as reference treatment since this registered the highest yield among all treatments.

of the weeds in the treated areas, these specific treatments exhibited a notable increase in their effectiveness in controlling weed growth. The maximum weed control efficiency was registered under oxadiargyl 75 g ha^{-1} PE *fb* HW 40 DAS (96.42%). The subsequent higher values were noted under IC *fb* HW at 20 & 40 DAS (95.49%) and oxadiargyl 100 g ha^{-1} PE (94.94%) which were superior over the rest of the treatments.

Growth, yield attributes and yield of dill
Among different weed control treatments, a treatment combination of oxadiargyl 75 g ha^{-1} pre-emergence followed by hand weeding at 40 DAS yielded the highest plant height (179.18 cm), dry matter accumulation (158.74 g) and branching intensity (7.35 branches per plant). Furthermore, this treatment exhibited superior reproductive growth, with the highest number of umbels per plant (12.22) and umbellets per plant (18.85) (Table 5). Notably, this treatment also achieved a 61.58% increase (Fig. 3) in seed yield (12.45 q ha^{-1}) compared to weedy check, underscoring the profound impact of effective weed management on crop productivity and it stood at par with T_{11} (11.53 q ha^{-1}) which was followed by T_4 (10.30 q ha^{-1}). In the case of straw yield, T_5 again led with 22.85 q ha^{-1} highlighting its capability to enhance overall biomass production and it was succeeded by T_{11} (19.89 q ha^{-1}).

Further, principal component analysis (Fig. 4) accounts for 90.9% of the variation in Dimension 1 and 7.8% in Dimension 2, emphasizing significant correlations between treatments and agronomic characteristics. Treatment T_{13} had the highest weed density and dry matter, resulting in suboptimal crop performance. Treatments T_5, T_4 and T_{11} exhibited superior seed output, plant height, and dry matter accumulation as a result of less weed pressure. An inverse association existed between weed density and agronomic qualities, with reduced weed burdens associated with increased output. T_5 and T_{11} exhibited optimal performance. However, T_{13} was the least successful owing to significant weed competition.

Economic assessment
Evaluating the economic aspects of weed management strategies in dill farming, such as herbicide use, manual weeding, or a combination, is crucial for maximizing returns. By assessing key economic parameters like benefit-cost ratio and net return, farmers can determine the most cost-effective and efficient weed control methods[36]. Herbicides reduce weed competition while manual weeding can help in cases where herbicides are less effective. A combined approach may further optimize weed control, enhance crop yields, and minimize financial risks, promoting sustainable farming practices in dill cultivation. This economic assessment also considers factors such as the timing and dosage of herbicide applications and the integration of manual weeding to reduce over-reliance on chemicals. By carefully calculating input costs and yield benefits, farmers can identify strategies that

Treatment	Plant height (cm)	Dry matter accumulation(g)	Branches plant^{-1}	Umbels plant^{-1}	Umbellets plant^{-1}	Yield (q ha^{-1})		Net return (USD ha^{-1})	B C ratio
						Seed	Straw		
T_1	157.92^{bcd}	137.69^{abcd}	6.13^{abcd}	10.32^{bc}	16.88^{abc}	9.31^{cd}	18.04^{bcd}	542.78^{cd}	1.63^{abcd}
T_2	160.41^{bcd}	140.84^{abcd}	6.21^{abcd}	10.81^{abc}	17.06^{abc}	9.52^{cd}	18.30^{bcd}	500.43^{cd}	1.27^{def}
T_3	158.26^{bcd}	123.15^{d}	5.73^{d}	10.16^{bc}	16.62^{bc}	8.84^{cde}	17.60^{bcd}	482.30^{cde}	1.38^{cdef}
T_4	172.74^{abc}	148.87^{abc}	6.80^{bc}	11.42^{abc}	17.43^{abc}	10.30^{bc}	19.12^{bc}	629.25^{bc}	1.85^{ab}
T_5	179.17^{a}	158.74^{a}	7.31^{a}	12.22^{a}	18.85^{a}	12.45^{a}	22.85^{a}	770.59^{a}	1.93^{a}
T_6	166.07^{abcd}	139.87^{abcd}	6.35^{abcd}	10.71^{abc}	17.16^{abc}	9.89^{bcd}	18.50^{bcd}	589.31^{bcd}	1.73^{abc}
T_7	162.04^{abcd}	135.39^{abcd}	5.91^{abcd}	10.24^{bc}	16.83^{abc}	8.98^{cde}	17.67^{bcd}	518.24^{cde}	1.58^{abcde}
T_8	154.83^{cd}	122.76^{d}	5.38^{d}	9.84^{bc}	16.10^{c}	8.23^{de}	16.47^{cd}	449.35^{de}	1.37^{cdef}
T_9	158.27^{bcd}	132.56^{bcd}	5.63^{bcd}	10.10^{bc}	16.53^{bc}	8.87^{cde}	17.44^{bcd}	444.94^{cde}	1.14^{ef}
T_{10}	156.83^{cd}	127.93^{cd}	5.52^{cd}	10.05^{bc}	16.47^{bc}	8.82^{cde}	17.34^{bcd}	484.65^{cde}	1.40^{cdef}
T_{11}	176.03^{ab}	154.52^{ab}	6.79^{ab}	11.61^{ab}	18.39^{ab}	11.53^{ab}	19.89^{b}	636.92^{ab}	1.44^{bcdef}
T_{12}	151.82^{d}	116.24^{de}	4.86^{de}	9.78^{c}	15.86^{c}	7.31^{e}	15.83^{d}	350.07^{e}	1.01^{f}
T_{13}	148.67^{d}	93.00^{e}	3.39^{e}	7.22^{d}	10.38^{d}	4.74^{f}	8.82^{e}	133.60^{f}	0.43^{g}

Table 5. Effect of weed management practices on growth, yield and economic parameters of dill at harvest (mean data of 2 years). Means with the same letter are not significantly different ($P \leq 0.05$) by Tukey's HSD test, while different letters indicate significant differences.
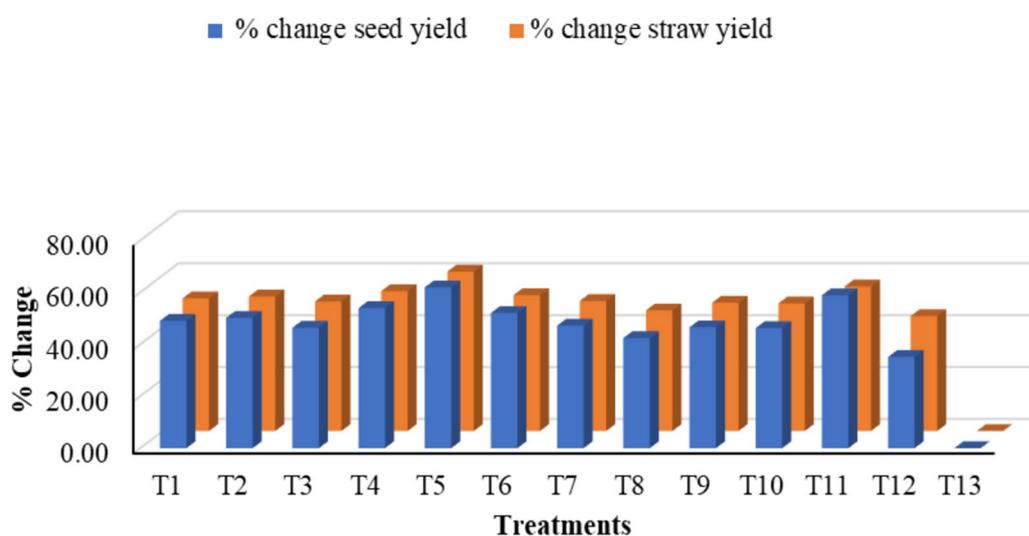

Fig. 3. Effect of various treatments on yield compared to weedy check.

maximize profit while mitigating risks associated with herbicide costs or labour expenses. The goal is to create a balanced and sustainable weed management system that aligns with environmental and economic goals.

Net return and B-C ratio.

It is evident that compared to weedy check where weeds were allowed to grow, there was an improvement in the net return of other treatments where weeds were controlled (Fig. 5). The treatment combination of oxadiargyl 75 g ha^{-1} pre-emergence followed by hand weeding at 40 DAS proved to be the most profitable, yielding a net return of USD 770.59 ha^{-1}, which represents an 85.66 and 17.34% increase over weedy check and IC *fb* HW at 20 & 40 DAS. This treatment also demonstrated a B-C ratio of 1.93, signifying a highly favourable return on investment. This suggests that farmers could potentially realize nearly double the amount invested for every rupee spent, emphasizing the economic viability of the approach (Table 5). The exceptional economic performance of the oxadiargyl 75 g ha^{-1} PE *fb* HW 40 DAS treatment can be attributed to the substantially higher seed yield achieved under this regime. Further analysis found that lower weed dry matter values enhance the B-C ratio and ultimately give better returns (Fig. 6)[37–39].

Although the treatment with oxadiargyl at 100 g ha^{-1} PE demonstrated good economic performance, with a net return of USD 629.25 ha^{-1} and a B-C ratio of 1.85, it failed to surpass the profitability of the integrated approach, which combined a slightly lower herbicide dose (75 g ha^{-1}) with subsequent hand weeding.
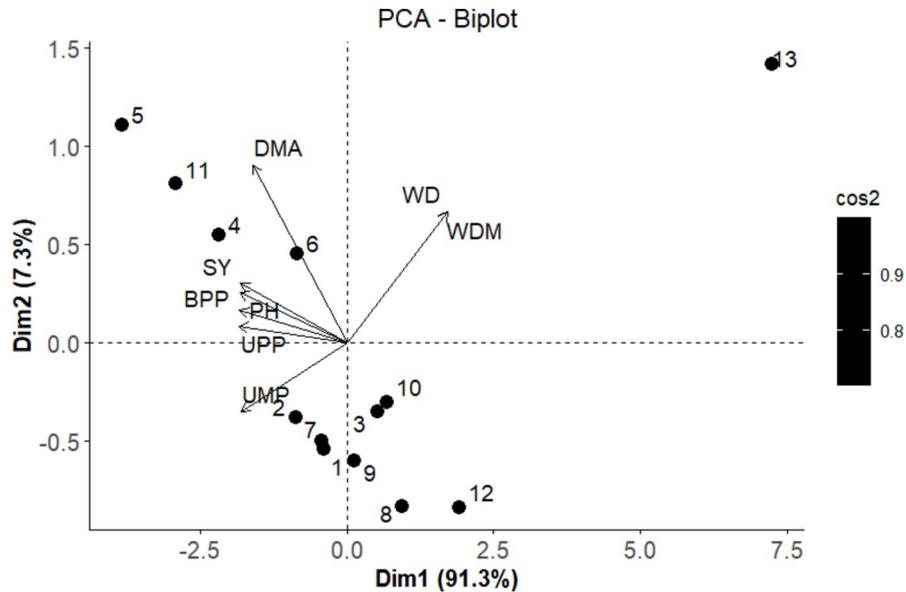
Fig. 4. Principal component analysis of total weed density (WD), total weed dry matter (WDM) per meter square, dry matter accumulation (DMA), plant height (PH), branches per plant (BPP), umbels per plant (UPP), umbellets per umbel (UMP) and seed yield (SY).
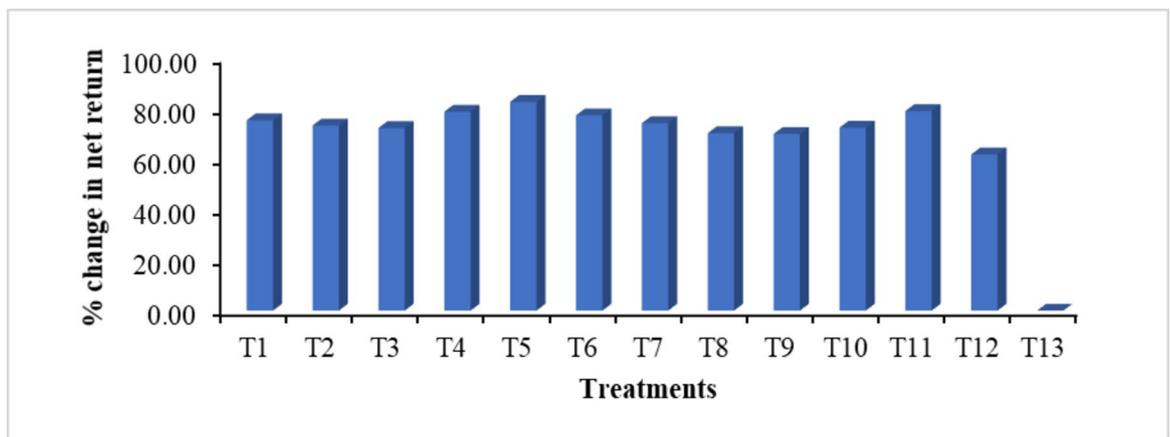

Fig. 5. Effect of various treatments on the net return compared to weedy check.

Discussion

Weed density, dry matter, weed control efficiency and weed index

Effective weed management plays a crucial role in reducing weed density and biomass, ultimately improving crop performance[40]. The present study demonstrated that pre-emergence application of oxadiargyl significantly lowered weed density and dry matter accumulation in comparison to weedy check where weeds were left uncontrolled[37,41,42]. The superior weed control efficiency observed in the present study is attributed to the residual activity of oxadiargyl, which forms a protective barrier on the soil surface inhibiting weed seed germination and emergence[43]. This broad-spectrum herbicide effectively suppresses both early and late weed flushes thereby providing prolonged weed control throughout the critical crop-weed competition phase[19,21,38]. The inclusion of hand weeding at 40 DAS further enhanced weed suppression, particularly for late-emerging weed species leading to higher weed control efficiency than treatments relying solely on herbicides[44,45]. A significant negative correlation was observed between the weed index and seed yield, suggesting that a reduction in the weed index (Fig. 7) led to a considerable improvement in crop productivity[46]. This relationship indicates that effective weed control measures reduced weed pressure and minimized competition for essential resources, resulting in a better crop growth environment[47]. Various findings also suggest that integrating pre-emergence herbicides with hand weeding provided comprehensive weed control, thereby enhancing yield attributes and lowering the weed index[11,48].
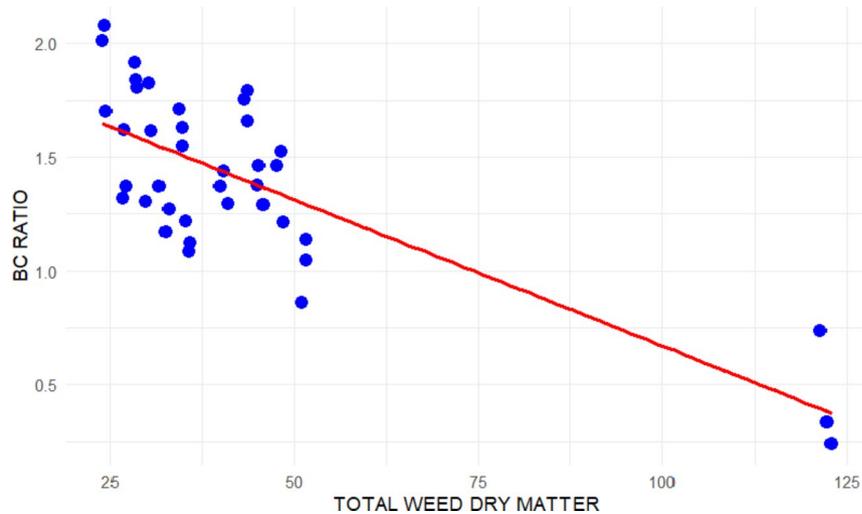
Fig. 6. Correlation between B C ratio and total weed dry matter. *In the above scatter plots blue points represent each data pair and a red trend line represents the linear fit.
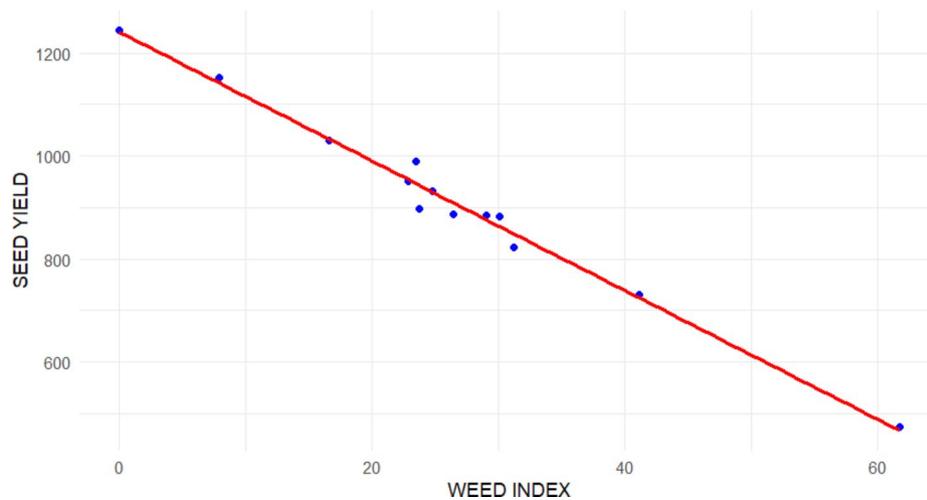

Fig. 7. Correlation between seed yield and weed index. *In the above scatter plots blue points represent each data pair and a red trend line represents the linear fit.

Effect on plant growth, dry matter accumulation and yield

The reduction in weed competition facilitated by pre-emergence herbicide application and subsequent weed control measures significantly influenced plant height, dry matter accumulation and yield[49]. The increased plant height and biomass accumulation observed in herbicide-treated plots were the direct outcomes of reduced weed competition[50]. As the availability of growth resources improved, the crop was able to allocate more energy toward its developmental processes, resulting in higher seed yield and improved yield components. Similar results have been reported by[51] who found that weed-free conditions led to optimal crop growth and yield maximization. Additionally[52], confirmed that the weedy check had the highest weed index, whereas herbicide treatments significantly reduced the weed index and improved weed control efficiency. The suppression of weed growth allowed the crop to utilize nutrients, moisture, and light more efficiently, leading to increased plant height, leaf area expansion, and biomass production[53,54]. These findings align with previous findings, which reported that herbicide treatments significantly influenced yield attribute parameters, including umbel density, number of seeds per umbel, 1000-seed weight, and overall seed yield[55]. In contrast, the untreated weedy check plots exhibited significant yield reductions due to uncontrolled weed competition[56]. Weeds competed with the main crop for moisture, space, nutrient and light and impeded crop growth through allelopathy, shading and physical obstruction[57]. Moreover, herbicides such as oxadiargyl inhibit critical biochemical pathways in weeds, particularly by disrupting porphyrin biosynthesis which is essential for photosynthesis and energy production[58]. This herbicidal action effectively reduced weed seed formation and weed indices, particularly for broadleaved weed species, which were dominant in the experimental field[59].

Net return and B-C ratio

The economic assessment of different weed management strategies in this study highlighted their substantial influence on crop productivity and profitability. The integration **of** pre-emergence herbicides, particularly oxadiargyl, with manual weeding, demonstrated the highest economic returns and benefit-cost ratio[60], . This combination effectively suppressed weed growth, reduced crop-weed competition and facilitated optimal resource utilization, resulting in higher seed yield and profitability[42]. The reduction in weed interference allowed the crop to absorb essential nutrients, moisture and light more efficiently, thereby enhancing overall productivity[61]. In contrast, plots maintained under weedy conditions exhibited significantly lower net returns primarily due to severe competition for resources, which negatively impacted plant growth and yield[62]. The limited branching and reduced plant height observed in untreated plots further emphasized the detrimental effects of unchecked weed growth on crop performance. The application of pre-emergence herbicides also reduced labour dependency for manual weeding, lowering operational costs and enhancing economic efficiency[63]. Effective weed control contributed to improved yields and optimized resource utilization, minimizing the need for additional inputs such as fertilizers and irrigation[64]. These strategies significantly reduced production costs while maximizing economic returns by ensuring uninterrupted access to available resources. These findings suggest that a holistic weed management strategy incorporating both chemical and physical methods can be more cost-effective than relying solely on herbicides[65]. The combined approach outperformed other treatments, highlighting the benefits of integrating multiple weed control methods to optimize economic return by balancing input costs with yield improvements[21,23,66,67].

Conclusion

Weeds pose significant challenges in dill cultivation by competing for essential resources such as nutrients, water, and light, which can severely reduce crop growth and yield potential. Additionally, the rapid proliferation of weeds, if left unmanaged, can lead to increased labour and production costs, ultimately affecting the profitability of dill farming. The integration of oxadiargyl at 75 g ha^{-1} as a pre-emergence herbicide combined with hand weeding at 40 DAS, has proven to be a highly effective strategy for weed management in dill cultivation. This approach has demonstrated significant reductions in both weed density and dry matter accumulation, leading to improved growth parameters and yield and yield attributes. The study strongly supports the adoption of integrated weed management practices, combining chemical and manual methods, to enhance crop productivity and profitability in dill farming. This approach reduces reliance on chemical herbicides and promotes sustainable farming practices by optimizing resource use and minimizing environmental impact. In conclusion, the integration of herbicides with timely hand weeding provides a robust and sustainable weed management strategy that enhances both the productivity and economic viability of dill cultivation.

Future research should focus on the long-term impacts of such integrated approaches on soil health, weed dynamics and overall crop productivity across different agro-ecological conditions. Additionally, assessing various herbicide formulations, timings and their interactions with other cultural practices could provide deeper insights into refining weed management strategies, thereby supporting the development of more sustainable agricultural practices.

Data availability

Data is provided within the manuscript.

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Author contributions

RC, AV and HS conceived and designed the research experiment. RC, MT and K contributed to data collection and performed field trials. RC, AV and HS assisted in data analysis and interpretation. All authors contributed to writing and reviewing the manuscript, approved the final version and agree to be accountable for all aspects of the work.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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