PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7652

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Assessment of different weed management practices on weed dynamics, growth and yield of Dill (*Anethum graveolens* L.)

Ruchika Choudhary[1], Arvind Verma[1*], Manish Tomar[2], Kannoj[3], Ritesh Patidar[1] & Lalchand Kumawat[1]

[1]Department of Agronomy, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan 313 001, India

[2]Department of Agronomy, CCS Haryana Agricultural University, Hisar, Haryana 125 004, India

[3]Forage Section, Department of Genetics and Plant Breeding, CCS Haryana Agricultural University, Hisar, Haryana 125 004, India

*Email: arnd_verma@rediffmail.com

OPEN ACCESS

ARTICLE HISTORY
Received: 08 February 2025
Accepted: 20 March 2025
Available online
Version 1.0 : 16 April 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Ruchika C, Arvind V, Manish T, Kannoj, Ritesh, Lalchand K. Assessment of different weed management practices on weed dynamics, growth and yield of Dill (*Anethum graveolens* L.). Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7652

Abstract

Dill (*Anethum graveolens* L.), a medicinal and seed spice crop, highly susceptible to weed competition due to its slow early growth, resulting in a significant production loss. Weed management is critical for improving crop output and quality. A two-season *rabi* 2020-21 & 2021-22 field experiment was conducted on the Agronomy Farm at Maharana Pratap University of Agriculture and Technology in Udaipur, Rajasthan to assess the impact of various weed management practices on weed dynamics, growth characteristics and yield. The study used a randomized block design with thirteen treatments, including pre-emergence (PE) and post-emergence (POE) herbicides, inter-cultivation and hand weeding. Pre-emergence spraying of oxadiargyl at 100 g ha^{-1} reduced weed density and dry matter accumulation, resulting in the maximum weed control efficiency (93.09 %) at 30 days after sowing (DAS). The use of oxadiargyl at 75 g ha^{-1} PE followed by hand weeding at 40 DAS, resulted in maximum biological yield to the tune of 35.3 per cent over weedy check. The combination of chemical and manual weed control was critical as it increased resource efficiency by lowering competition for nutrient, moisture and light availability, resulting in increased growth and seed yields. The research has implications for promoting integrated weed management (IWM) of dill in which a combination of herbicides and manual approaches best suppress weeds while maximizing crop performance. This becomes a more sustainable and economically viable choice for growers, reducing work intensity while minimizing long-term labour use and improving long-term weed management and production potential.

Keywords

dill; seed spices; weeds; weed management

Introduction

Dill (*Anethum graveolens* L.), an annual herbaceous plant of the Apiaceae family is globally recognized for its dual role as a spice and medicinal crop (1). Among the two major types, European dill (*A. graveolens*) and Indian dill (*A. sowa*) the latter is predominantly cultivated in South Asia and characterised by its distinct flavour and lower carvone content (2). Dill is believed to have originated in Southwest Asia or Southeast Europe and is now cultivated in temperate and subtropical regions including India, Pakistan, Germany, Hungary and the Netherlands (3). The plant's seeds and leaves are integral to various culinary traditions, contributing unique flavours to teas, pickles, sauces and confectioneries (4). Beyond its culinary applications, dill has significant pharmacological and nutritional value (5). The seeds are a rich source of carvone, a bioactive compound with potent antimicrobial properties and a natural inhibitor of potato sprouting (6). Additionally, the plant contains carotenoids, vitamin C and polyphenols (7) that vary in concentration across different growth stages highlighting its potential as a functional crop.

Despite its economic and agricultural importance, the cultivation of dill faces critical challenges particularly weed interference (8). Weed competition, especially during the early growth stages of the crop adversely impacts light, nutrient and moisture availability leading to reduced growth, diminished seed yield and compromised quality (9). Moreover, weeds can disrupt harvest efficiency, cause staining and lower the overall market value of dill seeds (10). Effective weed management is crucial to minimize these losses and ensure sustainable production however, this is particularly challenging for dill due to its slow and delayed germination (11). Weed management in dill traditionally involves chemical and physical methods. Hand -weeding, while effective, is labour-intensive, time-consuming and economically feasible only for small-scale farming operations (12). Pre-emergence herbicides can suppress weed germination but may fail to control weeds that emerge during the crop's early growth stages. These late-emerging weeds require additional management strategies such as post-emergence herbicides, inter-cultivation or repeated hand-weeding (13, 14). Integrated weed management (IWM), which combines mechanical, cultural and chemical methods, has been proposed as a viable solution to maintain weed levels below the economic threshold level, thereby enhancing crop productivity and quality (12).

Despite the potential benefits of IWM, existing research on dill has primarily focused on isolated weed control methods with limited emphasis on the dynamic interactions between weeds and the crop at various growth stages. Furthermore, the environmental and economic implications of weed management strategies, particularly in resource-constrained settings, remain underexplored. This study aims to bridge these gaps by evaluating the efficacy of integrated weed management practices in dill cultivation. The findings are expected to provide actionable insights for developing region-specific, sustainable and economically viable weed management strategies, contributing to improved productivity and the broader goals of sustainable agriculture.

Materials and Methods

Experimental site description and treatment details

The experiment was carried out over two consecutive *rabi* seasons at Agronomy Farm, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India (24°35'N latitude and 74°42'E at an altitude of 581.13 m AMSL). This site comes under agro-climatic zone IVa (Sub-Humid Southern Plain and Aravalli Hills). The soil was sandy clay loam with non-saline and a slightly alkaline pH of 8.05. The soil was medium in nitrogen content (318.64 kg ha^{-1}) and organic carbon content (0.56 %) along with high potassium content (465.55kg ha^{-1}). Udaipur experiences subhumid climatic conditions and has pronounced winters and only moderate summers. The average annual rainfall is around 637mm, mainly caused by the southwest monsoon between June and September (Fig. 1).

Dill variety 'Ajmer Sowa-1' (15) was sown in rows spaced 30 cm apart, at a seed rate of 3 kg ha^{-1}. Fertilization followed the recommended guidelines, applying 90 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1}. Herbicides were administered using a knapsack sprayer equipped with a flat fan nozzle, applying treatments with 500 litres of water (16). In treatments involving manual weed control, weeds were uprooted and removed at 40 DAS. Pre- emergence herbicides were sprayed at 0-3 DAS and post emergence herbicides were applied at 15 DAS (17). The research was carried out using a randomized block design (RBD) in three replication (18). The experiment comprised of thirteen treatments (Table 1) *viz.*, pendimethalin 1000 g ha^{-1}PE (T_1), pendimethalin 750 g ha^{-1}PE *fb* HW at 40 DAS (T_2), pendimethalin 750 g ha^{-1} PE quizalofop ethyl 40 g ha^{-1}PoE (T_3), oxadiargyl 100 g ha^{-1}PE (T_4), oxadiargyl 75 g ha^{-1}PE *fb* HW at 40 DAS (T_5), oxadiargyl 75 g ha^{-1}PE *fb* quizalofop ethyl 40 g ha^{-1}PoE (T_6), oxadiargyl 50 g ha^{-1} PoE (T_7), oxyfluorfen 100 g ha^{-1}PE (T_8), oxyfluorfen 75 g ha^{-1}PE *fb* HW at 40 DAS (T_9), oxyfluorfen 75 g ha^{-1}PE *fb* quizalofop ethyl 40 g ha^{-1}PoE (T_{10}), IC *fb* HW at 20 & 40 DAS (T_{11}), Oxadiargyl 50 g ha^{-1} + propaquizafop 50 g ha^{-1} PoE (T_{12}) and weedy check (T_{13}).

Analysis of weed density, weed dry matter and weed control efficiency

Weed density data were collected at 30 DAS using 0.5 m × 0.5 m quadrants per plot. These weed samples were then dried in an oven at 65 °C for 8 r and then dry matter was recorded (19). The data of weed density and dry matter were subjected to square root transformation (X + 0.5) to normalize their distribution (20) where "X" is the original

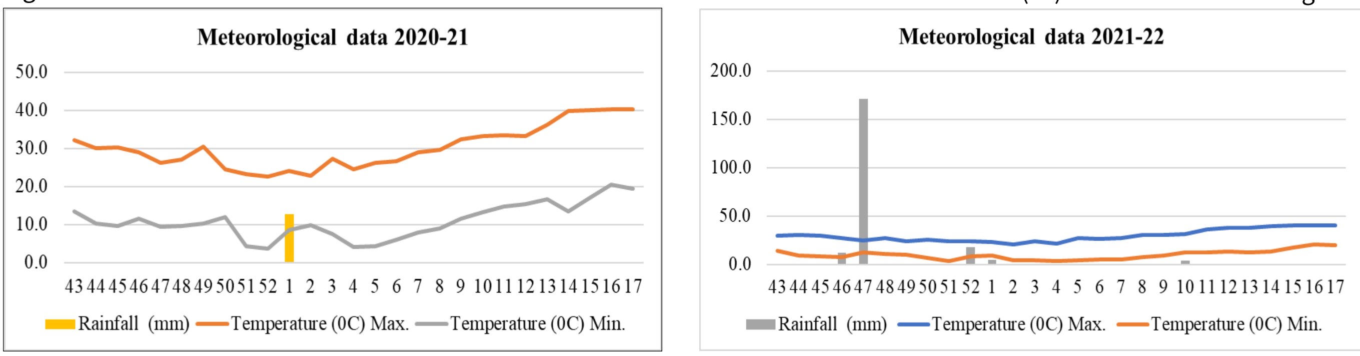

Fig. 1. Meteorological data for the experiment site during the experimental periods.

Source: AICRP on Agrometeorology, MPUAT, Udaipur

Table 1. Treatment details

Annotations	Treatments
T_1	Pendimethalin 1000 g ha^{-1} PE
T_2	Pendimethalin 750 g ha^{-1} PE *fb* HW 40 DAS
T_3	Pendimethalin 750 g ha^{-1} PE *fb* quizalofop ethyl 40 g ha^{-1} PoE
T_4	Oxadiargyl 100 g ha^{-1} PE
T_5	Oxadiargyl 75 g ha^{-1} PE *fb* HW 40 DAS
T_6	Oxadiargyl 75 g ha^{-1} PE *fb* quizalofop ethyl 40 g ha^{-1} PoE
T_7	Oxadiargyl 50 g ha^{-1} PoE
T_8	Oxyfluorfen 100 g ha^{-1} PE
T_9	Oxyfluorfen 75 g ha^{-1} PE *fb* HW 40 DAS
T_{10}	Oxyfluorfen 75 g ha^{-1} PE *fb* quizalofop ethyl 40 g ha^{-1} PoE
T_{11}	IC *fb* HW at 20 & 40 DAS
T_{12}	Oxadiargyl 50 g ha^{-1} + propaquizafop 50 g ha^{-1} PoE
T_{13}	Weedy check

data. Weed control efficiency (WCE %) were calculated considering weed dry matter by using standard formula suggested (21).

$$\text{WCE (\%)} = \frac{\text{DMC-DMT}}{\text{DMC}} \times 100 \qquad \text{(Eqn.1)}$$

Analysis of growth, yield and yield attributes

Growth and yield parameters were evaluated using five randomly selected plants from each treatment. At harvest maturity, yield was measured on a per hectare basis. After threshing, the seed and straw yields of dill were recorded for each treatment plot and the results were expressed in quintals per hectare (q ha^{-1}). The seed and straw yield were summed up to obtain biological yield.

Statistical analysis

The collected data were analysed through analysis of variance (ANOVA) followed by an F-test. Mean differences were compared using the Tukey HSD test at a 5 % significance level. All statistical analyses were performed using R Studio software, version 1.3.1093(22). Weed density and dry matter data were normalized using square root transformation [√ (X + 0.5)] where "X" represents the original values.

Results and Discussion

Effect on weeds

The experimental field was primarily infested with broadleaved weeds representing 84.99 % of the total weed population while grassy weeds comprised 14.99 % (Fig. 2). The broadleaved species included *Chenopodium album*, *Chenopodium murale*, *Melilotus indica*, *Malva parviflora*, *Fumaria parviflora* and *Convolvulus arvensis* while *Phalaris minor* was sole grassy weed observed (23-26). Different weed control treatments reduced weed density and dry matter of different weeds. Among the various control treatments, pre-emergence application of oxadiargyl at 100 g ha^{-1} exhibited the lowest weed density and dry matter for both grassy and broadleaved weeds (Table 2-4). This treatment proved to be the most effective in weed control at 30 DAS. The remarkable effectiveness of oxadiargyl is due to its broad-spectrum action, primarily employed as a pre-emergence herbicide. It forms a protective barrier on the soil surface, preventing the germination and emergence of weed seeds. Its prolonged activity in the soil ensures sustained efficacy, facilitating the control of early and late-emerging weed flushes. This extended period of weed suppression is crucial during the critical stages of crop-weed competition, reducing resource competition and supporting optimal crop growth. As a result, oxadiargyl plays a vital role in comprehensive weed management contributing significantly to improved agricultural outcomes (27-29). This treatment was closely followed with inter-cultivation followed by hand weeding at 20 and 40 DAS. The superior performance of these treatments can be attributed to their ability to manage a broad spectrum of weeds including both grassy and broadleaved species through the application of pre-emergence herbicides and inter-culture practices (30, 31). Further, oxadiargyl @ 75 g ha^{-1} combined with hand weeding at 45 DAS resulted in lower weed parameters highlighting the superiority of integration of pre-emergence herbicides with hand weeding. The combined use of pre-emergence herbicides and timely hand weeding at specific intervals effectively bridged the gap in weed control, ensuring comprehensive management of both early and late-emerging weed flushes.

The highest weed control efficiency of grassy (93.78 %), broadleaved (92.98 %) and total weeds (93.09 %) was observed in oxadiargyl at 100 g ha^{-1}. The subsequent trend was witnessed in IC *fb* HW at 20 & 40 DAS of grassy (89.53 %), broadleaved (91.54 %) and total weeds (91.26 %).

Growth, yield attributes and yield

At 30 DAS, the treatment with oxadiargyl at 100 g ha^{-1} PE recorded the highest plant height and dry matter, comparable to the treatment involving inter-cultivation followed by hand weeding at 20 and 40 DAS (Table 5). The improvement can be attributed to reduced weed competition which increases the availability of essential resources such as nutrients, soil moisture and light. This favourable resource allocation enhances crop growth characteristics including improved stature, expanded leaf area and increased biomass production. With minimal competition from neighbouring plants, the crop can effectively channel resources toward its growth and development resulting in overall better plant performance.

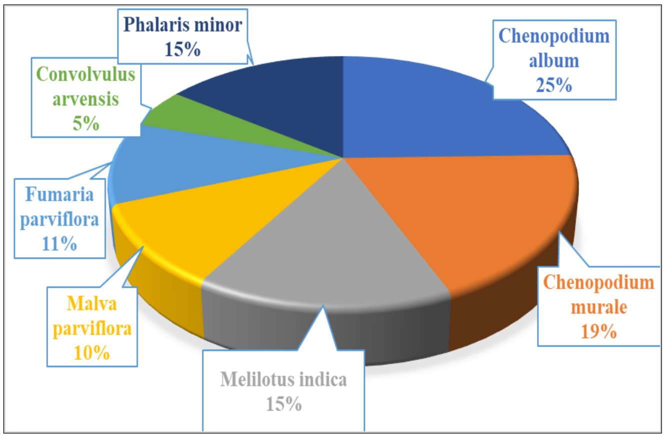

Fig. 2. Relative weed composition (%) of the experiment field.

Table 2. Effect of weed management on weed density at 30 DAS

Treatments	Weed density (No. m^{-2})						
	Chenopodium Album	***Chenopodium Murale***	***Fumaria parviflora***	***Convolvulus arvensis***	***Phalaris minor***	***Melilotus indica***	***Malva parviflora***
T_1	1.33(1.26)^{efg}	1.47(1.67)^{cde}	1.64(2.20)^{b}	1.23(1.03)^{g}	1.59(2.03)^{bcd}	1.38(1.42)^{cde}	1.30(1.19)^{bcd}
T_2	1.36(1.34)^{ef}	1.53(1.86)^{cde}	1.74(2.53)^{b}	1.33(1.28)^{ef}	2.01(3.55)^{bcd}	1.48(1.69)^{cde}	1.32(1.24)^{bcd}
T_3	1.64(2.20)^{c}	1.69(2.35)^{bcd}	2.28(4.72)^{b}	1.50(1.76)^{c}	1.66(2.27)^{bcd}	1.89(3.06)^{bcd}	1.65(2.23)^{bcd}
T_4	1.03(0.59)^{h}	1.26(1.09)^{e}	1.55(1.90)^{b}	1.15(0.81)^{h}	1.15(0.83)^{d}	1.12(0.80)^{e}	1.02(0.54)^{d}
T_5	1.13(0.77)^{gh}	1.41(1.48)^{de}	1.64(2.20)^{b}	1.24(1.03)^{g}	1.49(1.73)^{bcd}	1.28(1.13)^{de}	1.15(0.82)^{bcd}
T_6	1.61(2.10)^{cd}	1.65(2.23)^{bcd}	2.25(4.58)^{b}	1.45(1.60)^{cd}	1.47(1.67)^{bcd}	1.58(2.00)^{bcde}	1.59(2.02)^{bcd}
T_7	1.18(0.88)^{fgh}	1.43(1.55)^{de}	1.66(2.27)^{b}	1.25(1.07)^{fg}	1.95(3.28)^{bcd}	1.37(1.37)^{de}	1.25(1.06)^{bcd}
T_8	1.36(1.36)^{ef}	1.55(1.91)^{cde}	2.06(3.75)^{b}	1.37(1.38)^{de}	1.72(2.47)^{bcd}	1.49(1.73)^{cde}	1.36(1.36)^{bcd}
T_9	1.39(1.44)^{de}	1.58(1.98)^{cde}	2.10(3.93)^{b}	1.38(1.42)^{de}	2.05(3.69)^{bcd}	1.55(1.89)^{bcde}	1.53(1.83)^{bcd}
T_{10}	2.06(3.76)^{b}	1.83(2.86)^{bc}	2.38(5.16)^{b}	1.63(2.18)^{b}	1.91(3.17)^{bc}	1.96(3.32)^{bc}	1.79(2.72)bc
T_{11}	1.10(0.72)^{h}	1.34(1.29)^{de}	1.60(2.05)^{b}	1.21(0.97)^{gh}	1.38(1.40)^{cd}	1.25(1.06)e	1.12(0.76)^{cd}
T_{12}	2.12(4.00)^{b}	1.93(3.23)^{b}	2.56(6.08)^{b}	1.72(2.45)^{b}	2.19(4.30)^{b}	2.09(3.87)^{b}	1.85(2.92)^{b}
T_{13}	4.90(23.52)^{a}	4.33(18.23)^{a}	3.27(10.18)^{a}	2.34(4.97)^{a}	3.85(14.34)^{a}	3.85(14.35)^{a}	3.24(10.02)^{a}

Data subjected to $\sqrt{x + 0.5}$ transformation and figures in parenthesis are original weed count per sq. m

Table 3. Effect of weed management on weed dry matter at 30 DAS

Treatments	Weed dry matter (g m^{-2})						
	Chenopodium album	***Chenopodium murale***	***Fumaria parviflora***	***Convolvulus arvensis***	***Phalaris minor***	***Melilotus indica***	***Malva parviflora***
T_1	1.03(0.57)^{d}	1.12(0.76)^{efg}	1.24(1.05)^{g}	1.01(0.52)^{ef}	1.23(1.00)^{fg}	1.08(0.66)^{def}	1.22(1.01)^{bc}
T_2	1.05(0.61)^{d}	1.16(0.85)^{def}	1.31(1.22)^{f}	1.06(0.62)^{de}	1.48(1.70)^{bcd}	1.15(0.83)^{def}	1.50(1.83)^{bc}
T_3	1.22(0.99)^{c}	1.26(1.08)^{c}	1.64(2.18)^{d}	1.17(0.88)^{c}	1.25(1.07)^{efg}	1.38(1.42)^{bc}	1.92(3.33)^{b}
T_4	0.87(0.27)^{f}	1.00(0.49)^{h}	1.18(0.89)^{h}	0.95(0.41)^{f}	0.96(0.42)^{h}	0.95(0.41)^{f}	1.00(0.50)^{c}
T_5	0.92(0.35)^{ef}	1.08(0.67)^{fgh}	1.25(1.05)^{g}	1.01(0.52)^{ef}	1.18(0.88)^{fg}	1.05(0.59)^{def}	1.06(0.63)^{c}
T_6	1.20(0.95)^{c}	1.24(1.05)^{cd}	1.63(2.16)^{d}	1.13(0.77)^{cd}	1.16(0.84)^{fg}	1.25(1.05)^{cd}	1.56(1.95)^{bc}
T_7	0.95(0.40)^{e}	1.10(0.71)^{efg}	1.26(1.10)^{g}	1.03(0.56)^{def}	1.42(1.51)^{cde}	1.08(0.67)^{def}	1.37(1.46)^{bc}
T_8	1.06(0.62)d	1.17(0.87)^{cde}	1.49(1.73)^{e}	1.12(0.76)^{cd}	1.32(1.25)^{def}	1.17(0.87)^{cde}	1.29(1.33)^{bc}
T_9	1.07(0.65)^{d}	1.19(0.91)^{fde}	1.53(1.83)^{e}	1.09(0.69)^{cde}	1.53(1.86)^{bc}	1.20(0.93)^{cde}	1.70(2.42)^{bc}
T_{10}	1.50(1.77)^{b}	1.36(1.34)^{b}	1.75(2.56)^{c}	1.28(1.16)^{b}	1.45(1.61)^{cd}	1.47(1.65)^{b}	1.66(2.25)^{bc}
T_{11}	0.91(0.33)^{ef}	1.04(0.59)^{gh}	1.23(1.02)^{g}	1.00(0.51)^{ef}	1.10(0.71)^{gh}	1.00(0.50)^{ef}	1.07(0.64)^{c}
T_{12}	1.52(1.81)^{b}	1.40(1.47)^{b}	1.84(2.88)^{b}	1.32(1.24)^{b}	1.63(2.17)^{b}	1.52(1.80)^{b}	1.71(2.43)^{bc}
T_{13}	3.36(10.77)^{a}	3.00(8.50)^{a}	2.27(4.65)^{a}	1.73(2.51)^{a}	2.70(6.78)^{a}	2.82(7.46)^{a}	2.99(8.46)^{a}

Data subjected to $\sqrt{x + 0.5}$ transformation and figures in parenthesis are original weed dry matter per sq. m

Table 4. Effect of weed management practices on weed density and weed dry matter at 30 DAS

Treatments	Weed density (m^{-2})			Weed dry matter ($g\ m^{-2}$)			Weed control efficiency (%)		
	Grassy	Broadleaved	Total	Grassy	Broadleaved	Total	Grassy	Broadleaved	Total
T_1	1.59(2.03)^{de}	3.04(8.77)^{gh}	3.36(10.80)^{g}	1.23(1.00)^{fg}	2.25(4.57)^{fg}	2.46(5.58)^{fgh}	85.19	89.21	88.65
T_2	2.01(3.55)^{c}	3.23(9.93)^{g}	3.74(13.48)^{f}	1.48(1.70)^{bcd}	2.54(5.96)^{ef}	2.85(7.66)^{def}	74.88	85.94	84.41
T_3	1.66(2.27)^{d}	4.10(16.31)^{d}	4.37(18.58)^{d}	1.25(1.07)^{efg}	3.21(9.88)^{bcd}	3.37(10.94)^{bc}	84.29	76.69	77.74
T_4	1.15(0.83)^{g}	2.49(5.73)^{k}	2.65(6.56)^{i}	0.96(0.42)^{h}	1.86(2.97)^{g}	1.97(3.40)^{i}	93.78	92.98	93.09
T_5	1.49(1.73)^{ef}	2.82(7.45)^{ij}	3.11(9.17)^{h}	1.18(0.88)^{fg}	2.08(3.81)^{g}	2.28(4.70)^{ghi}	86.95	90.99	90.44
T_6	1.47(1.67)^{ef}	3.88(14.53)^{e}	4.09(16.20)^{e}	1.16(0.84)fg	2.90(7.93)^{cde}	3.04(8.78)^{cde}	87.58	81.27	82.14
T_7	1.95(3.28)^{c}	2.95(8.20)^{hi}	3.46(11.49)^{g}	1.42(1.51)^{cde}	2.32(4.90)^{fg}	2.63(6.42)^{efg}	77.70	88.42	86.94
T_8	1.72(2.47)^{d}	3.46(11.50)^{f}	3.80(13.97)^{f}	1.32(1.25)^{def}	2.58(6.18)^{ef}	2.81(7.43)^{def}	81.57	85.42	84.88
T_9	2.05(3.69)^{bc}	3.61(12.50)^{f}	4.09(16.19)^{e}	1.53(1.86)^{bc}	2.81(7.42)^{de}	3.13(9.28)^{cd}	72.59	82.47	81.11
T_{10}	1.91(3.17)^{c}	4.53(20.01)^{c}	4.87(23.18)^{c}	1.45(1.61)^{cd}	3.35(10.73)^{bc}	3.58(12.34)^{b}	76.26	74.68	74.89
T_{11}	1.38(1.40)^{f}	2.71(6.85)^{j}	2.96(8.24)^{h}	1.10(0.71)^{gh}	2.02(3.58)^{g}	2.19(4.29)^{hi}	89.53	91.54	91.26
T_{12}	2.19(4.30)^{b}	4.80(22.56)^{b}	5.23(26.85)^{b}	1.63(2.17)^{b}	3.48(11.64)^{b}	3.78(13.81)^{b}	67.99	72.52	71.90
T_{13}	3.85(14.4)^{a}	9.04(81.27)^{a}	9.80(95.61)^{a}	2.70(6.78)^{a}	6.55(42.36)^{a}	7.05(49.14)^{a}	0.00	0.00	0.00

Data subjected to $\sqrt{x + 0.5}$ transformation and figures in parenthesis are original weed count and weed dry matter per sq. m

Table 5. Effects of weed management on plant growth, yield attributes and yield

Treatments	Plant height (cm)	Plant dry matter (g)	Seed yield $plant^{-1}$ (g)	Test weight (g)	Biological yield ($q\ ha^{-1}$)
	30 DAS				
T_1	38.37^{bc}	7.14^{abcd}	3.29^{bcde}	3.77^{abcd}	27.35^{cd}
T_2	37.57^{bc}	6.43^{cd}	3.45^{abcd}	3.85^{abcd}	27.82^{cd}
T_3	35.76^{c}	7.04^{abcd}	3.05^{cde}	3.63^{bcde}	26.44^{cde}
T_4	44.25^{a}	8.22^{a}	3.82^{ab}	4.20^{abc}	29.41^{bc}
T_5	39.47^{abc}	7.10^{abcd}	3.98^{a}	4.39^{a}	35.3^{a}
T_6	39.68^{abc}	7.42^{abc}	3.59^{abc}	3.94^{abcd}	28.39^{bc}
T_7	36.07^{c}	6.93^{abcd}	3.08^{cde}	3.71^{bcde}	26.65^{cd}
T_8	35.80^{c}	6.44^{cd}	2.88^{de}	3.48^{de}	24.7^{de}
T_9	34.82^{c}	6.79^{bcd}	2.98^{de}	3.54^{cde}	26.31^{cde}
T_{10}	36.74^{c}	6.73^{bcd}	2.93^{de}	3.51^{de}	26.16^{cde}
T_{11}	42.73^{ab}	7.76^{ab}	3.88^{ab}	4.25^{ab}	31.42^{b}
T_{12}	34.92^{c}	6.29^{cd}	2.87^{de}	3.43^{de}	23.14^{e}
T_{13}	34.27^{c}	6.09^{d}	2.75^{e}	3.05^{e}	13.56^{f}

Data subjected to $\sqrt{x + 0.5}$ transformation and figures in parenthesis are original weed count and weed dry matter per sq. m

Further, enhanced yield attributes namely test weight and seed yield per plant were observed with the application of oxadiargyl @ 75 g ha^{-1} combined with hand weeding at 45 DAS can be attributed to the effective suppression of grassy and broadleaved weeds. This reduced weed competition likely allowed the crop to efficiently utilize the available soil nutrients and moisture, ultimately leading to improved yield attributes and higher seed yield in the spice crop. As shown in Table 4, the treatment with oxadiargyl at 75 g ha^{-1} PE followed by hand weeding at 40 DAS achieved the highest biological yield, followed by inter-cultivation with hand weeding at 20 and 40 DAS and oxadiargyl at 100 g ha^{-1} PE. This was followed by treatment T_{11} achieved subsequent improvement in biological yield where weeds were managed effectively highlighting its superior efficacy. A similar trend can be witnessed in rest of the treatments as compared to weedy check (T_{12}) which registered lowest yields highlighting the importance of weed management (Fig. 3). The significant improvement in yield can be attributed to the combined effects of inter cultivation and hand weeding as well as the integration of herbicides with hand weeding which collectively enhanced yield attributes and subsequently the seed yield of dill (24, 32-35).

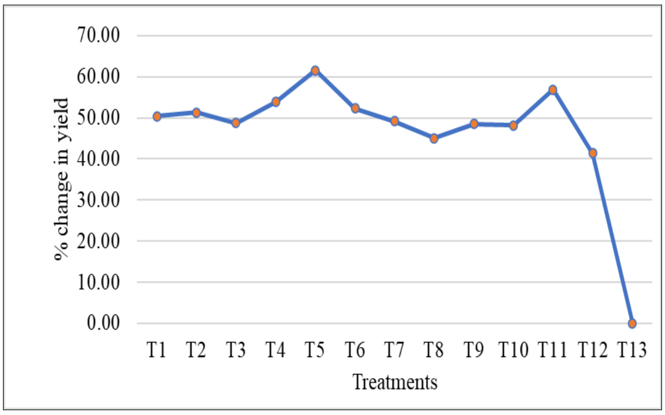

Fig. 3. Per cent change in biological yield as compared to weedy check (T_{13}).

This treatment improved the source-sink relationship by effectively controlling weeds during the critical crop-weed competition period, enhancing yield and associated attributes. Integrating physical and chemical weed control methods proved highly effective in minimizing weed interference creating favourable conditions for optimizing crop growth and productivity (30, 34, 36). In contrast, substantial yield reductions in the weedy check plots were primarily due to resource competition, allelopathic effects, shading and physical obstruction caused by weeds. Certain herbicides such as oxadiargyl effectively target critical biochemical pathways in weeds including the inhibition of proto-porphyrinogen oxidase in porphyrin biosynthesis. This disruption hampers photosynthesis and energy translocation, reducing seed formation and weed indices. Such mechanisms are particularly effective against the broadleaf weed species prevalent in the experimental field (37).

The PCA biplot (Fig. 4) presents the interrelations between treatments (T_1-T_{13}) and variables. Dim1 (81.2 %) and Dim2 (12.3 %) explained 93.5 % of the variance. Treatments T_4 and T_5 showed higher values for BY, TW and DMA, therefore better productivity. In contrast, T_{13} is an outlier with a higher value of WD and WDM, indicating poor weed management and damage to productivity. A negative correlation between weed parameters (WD, WDM) and yield-related traits (BY, TW) suggests the importance of effective weed control in better growth and development of crops.

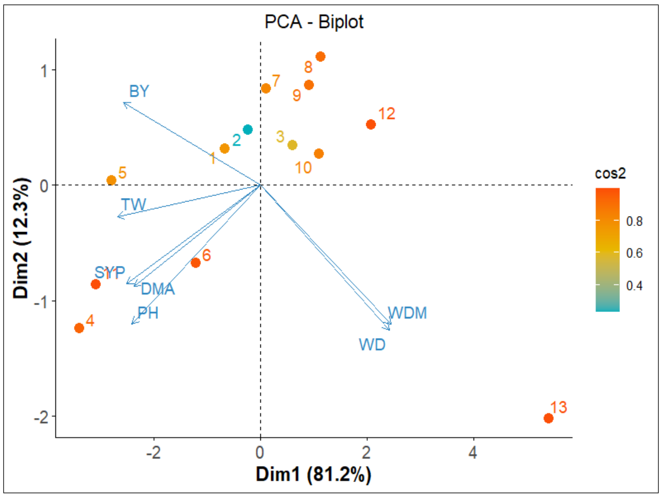

Fig. 4. Principal component biplot of different variables.

Where, WD (Weed Density), WDM (Weed Dry Matter), PH (Plant Height), DMA (Dry Matter Accumulation), TW (Test Weight), SYP (Seed Yield per Plant) and BY (Biological Yield)

Conclusion

Weed control is of prime importance to improve the productivity and quality of dill (*Anethum graveolens* L.), particularly because of its slow initial growth and sensitivity to competition from weeds. The results of the present study highlight the highest efficiency of pre-emergence application of oxadiargyl at 100 g ha^{-1}, which recorded maximum efficiency of weed control (93.09 %) by reducing weed density and dry matter accumulation by significant amounts at 30DAS. In addition, interaction of oxadiargyl at 75 g ha^{-1} PE with hand weeding at 40 DAS registered maximum biological yield, which identified the advantage of implementing a combination of chemical and manual methods of weed control. The study brings to the prominence the adoption of integrated weed management (IWM) as a cost-effective and environmentally benign strategy for the cultivation of dill. Optimizing resource availability and minimizing competition for nutrients, water and light, the IWM operations maximize the crop growth and potential yield and decrease the dependency on labour-based operations. With the emerging problem of resistance to herbicides and environmental concerns, the optimal combination of chemical and non-chemical strategies of weed control is required to ensure long-term suppression of weeds. Future research needs to target optimization of the dose rates of herbicides, evaluation of weed control efficacy of eco-friendly options and long-term implication of IWM on soil health and crop productivity. Implementation of these practices can play a long way in sustainable production of dill, which will assure improved profitability for the farmer while maintaining the ecological balance.

Authors' contributions

RC, AV, MT, K, RP and LK contributed equally to the manuscript's ideation, conceptualization, resource collection and writing. They collaborated on drafting and refining the content to ensure clarity and coherence. AV provided supervision throughout the process, offering guidance and feedback to enhance the paper's quality and relevance. All authors actively engaged in discussions, revisions and final approval for publication, collectively producing a comprehensive review on weed control strategies for seed spices production and agricultural sustainability.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interests.

Ethical issues: None

References

1. Kirici S, Bayram E, Inan M, Kaya DA, Özel A. Traditional farming of Apiaceae species in Türkiye: *Pimpinella anisum* L., *Foeniculum vulgare* Mill., *Cuminum cyminum* L. In Medicinal and Aromatic Plants of Turkey. 2023;(pp. 241-281). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-43312-2_12

2. Lal G, Malhotra SK, Lal S, Meena SS. Minor seed spices: Ajwain, Dill, Celery and Aniseed. Handbook of Spices in India: 75 Years of Research and Development, Singapore: Springer Nature Singapore; 2024, p. 3505–37. https://doi.org/10.1007/978-981-19-3728-6_53

3. Renfrew J, Sanderson H. Herbs and vegetables. In The cultural history of plants. 2012, (pp. 101-135). Routledge. https://doi.org/10.4324/9780203020906

4. Aggarwal R, Bains K. Spices in Culinary Art. Handbook of Spices in India: 75 Years of Research and Development, Singapore: Springer Nature Singapore; 2024, p. 917–54. https://doi.org/10.1007/978-981-19-3728-6_16

5. Masoody IH Al, Alarkwazi RK, Yasssiry AS Al. Pharmaceutical and biological properties of Dill: A review. IOP Conference Series: Earth and Environmental Science 2023;1158:062005. https://doi.org/10.1088/1755-1315/1158/6/062005

6. Shekhawat G, Jana S. *Anethum graveolens*: An Indian traditional medicinal herb and spice. Pharmacognosy Reviews 2010;4:179. https://doi.org/10.4103/0973-7847.70915

7. Giordano M, Petropoulos SA, Kyriacou MC, Graziani G, Zarrelli A, Rouphael Y, et al. Nutritive and phytochemical composition of aromatic microgreen herbs and spices belonging to the Apiaceae family. Plants. 2022;11:3057. https://doi.org/10.3390/plants11223057

8. Awasthi P, Joshi D, Bogati S, Bhandari R. Production and commercialization of Dill (*Anethum graveolens* Linn). SSRN Electronic Journal. 2022. https://doi.org/10.2139/ssrn.4170531

9. Kaur S, Kaur R, Chauhan BS. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Protection. 2018;103:65–72. https://doi.org/10.1016/J.CROPRO.2017.09.011

10. Kumar S, Kumari S, Rana SS, Rana RS, Anwar T, Qureshi H, et al. Weed management challenges in modern agriculture: The role of environmental factors and fertilization strategies. Crop Protection. 2024;185:106903. https://doi.org/10.1016/j.cropro.2024.106903

11. Pickett KM, Zheljazkov VD. Screening of preemergence and postemergence herbicides for weed control in dill (*Anethum graveolens*), Fennel (*Foeniculum vulgare*), coriander (*Coriandrum sativum*) and basil (*Ocimum basilicum*). ACS Symposium Series, vol. 1218, American Chemical Society; 2016, p. 103–19. https://doi.org/10.1021/bk-2016-1218.ch008

12. Amini R, Abbaszadeh M, Khoshmaram L. Performance of integrating reduced trifluralin doses with nonchemical treatments on weed management and dill (*Anethum graveolens* L.) yield. Crop Protection. 2023;168:106233. https://doi.org/10.1016/j.cropro.2023.106233

13. Elkoca E, Kantar F, Zengin H. Effects of chemical and agronomical weed control treatments on weed density, yield and yield parameters of Lentil *(Lens culinaris* L. Cv. Erzurum-89). Asian Journal of Plant Sciences. 2004;3:187–92. https://doi.org/10.3923/ajps.2004.187.192

14. Patel BD, Chaudhari DD, Patel VJ, Patel HK. Integrated weed management in fennel production system and its residual effect on succeeding summer greengram. Indian Journal of Weed Science. 2019;51:368. https://doi.org/10.5958/0974-8164.2019.00077.7

15. Yadav OP, Khariwal IS, Rai KN, Kumar D, Henry A, Mahala HR, et al. Genetic resources and improvement of crops, seed spices, grasses, trees and horticultural crops for Arid zone. In: Kar A, Garg BK, Singh MP, Kathju S, editors. Trends in Arid Zone Research in India, Director, Central Arid Zone Research Institute, Jodhpur 342 003; 2009, p. 238–77.

16. Jat NK, Singh D V. Weed control efficacy of different post-emergence herbicides in mungbean (*Vigna radiata*) in hot arid regions. Indian Journal of Agronomy. 2021;66:438–43.

17. Kumar S, Shivani, Mishra JS, Kumar S, Kumar U, Bharati RC. Efficacy of pre- and post-emergence herbicides on complex weed flora in direct-seeded rice (*Oryza sativa*) in the eastern plains. Indian Journal of Agricultural Sciences. 2018;88:387–92. https://doi.org/10.56093/ijas.v88i3.78502

18. Sahai H, Ageel MI. Some simple experimental designs. The Analysis of Variance, Boston, MA: Birkhäuser Boston; 2000, p. 483–542. https://doi.org/10.1007/978-1-4612-1344-4_10

19. Rashid HU, Khan A, Hassan G, Khan SU, Saeed M, Khan SA, et al. Weed suppression in maize (*Zea mays* L.) through the allelopathic effects of sorghum [*Sorghum bicolor* (L.) Conard moench.], sunflower (*Helianthus annuus* L.) and parthenium (*Parthenium hysterophorus* L.) plants. Applied Ecology and Environmental Research. 2020;18:5187–97. https://doi.org/10.15666/aeer/1804_51875197

20. Gomez KA, Gomez AA. Statistical procedures for agricultural research. John Wiley & Sons; 1984.

21. Mani VS, Gautam KC, Chakraborty TK. Losses in crop yield in India due to weed growth. Pest Articles and News Summaries, Section C: Weed Control 1968;14:142–58. https://doi.org/10.1080/05331856809432575

22. Soares DO, Pinto KG, Bhowmik PC, Albertino SM. Chemical properties of soil and cassava yield as a function of weed management by cover crops in the Amazon ecosystem. Sustainability. 2022;14:1886. https://doi.org/10.3390/su14031886

23. Kumar R, Malik YP, Punia SS. Weed control in fenugreek with pendimethalin and imazethapyr. Indian Journal of Weed Science. 2016;48:225. https://doi.org/10.5958/0974-8164.2016.00056.3

24. Malunjkar BD, Verma A, Choudhary R, Choudhary RS, Kaushik MK, Mali GR. Production of fenugreek (*Trigonella foenum-graecum*) as influenced by weed management practices and vermicompost application. Legume Research. 2022;45:68–72. https://doi.org/10.18805/LR-4363

25. Punia SS, Tehlan S. Bioefficacy of different herbicides in fenugreek. Indian Journal of Weed Science. 2017;49:298. https://doi.org/10.5958/0974-8164.2017.00079.x

26. Singh N, Mundra SL, Kaushik MK. Production potential of fenugreek as influenced by weed management practices. Indian Journal of Weed Science. 2014;46:197–9.

27. Choudhary M, Shivran A, Lakhran H, Verma H, Choudhary S, Doodhwal K, et al. Effect of plant geometry and weed management on growth and yield of fennel (*Foeniculum vulgare* Mill.) under semi-arid conditions of Rajasthan. Indian Journal of Agronomy. 2021;66:216–22. https://doi.org/10.59797/ija.v66i2.2842

28. Gohil BS, Mathukia RK, Dobariya VK, Chhodavadia SK. Weed management and dynamics of weed seed bank in fennel. Indian Journal of Weed Science 2014;46:399–401.

29. Meena SS, Mehta RS, Lal G, Anwer MM. Economic feasibility of weed management practices in fenugreek. Indian Journal of Horticulture 2013;70:150–3.

30. Mehriya ML, Yadav RS, Jangir RP, Poonia BL. Nutrient utilization by cumin (*Cuminum cyminum*) and weeds as influenced by different weed-control methods. Indian Journal of Agronomy. 2007;52:176–9. https://doi.org/10.59797/ija.v52i2.4920

31. Yadav SS, Sharma OP, Kumawat PD, Yadav RD. Effect of weed control and nitrogen on yield, nutrient removal and quality parameters of cumin (*Cuminum cyminum* L.). Journal of Spices and Aromatic Crops. 2004;13:22–7.

32. Fagaria VD, Gupta KC, Saxena R. Integrated weed management in fenugreek (*Trigonella foenum graecum* L.) in semi arid regions of Rajasthan. International Journal of Agricultural Sciences. 2014;10:302–4.

33. Meena SS, Mehta RS. Economic feasibility of weed management practices in cumin. Indian Journal of Horticulture. 2010;67:189–92.

34. Singh I, Rathore MS, Mehriya ML, Chawra RS. Bio-efficacy of herbicides applied in cumin (*Cuminum cyminum*) and their carry over effects on succeeding pearlmillet (Pennisetum glaucum). Indian Journal of Agronomy 2013;58:490–4. https://doi.org/10.59797/ija.v58i4.4255

35. Tiwari RC, Bairwa RC, Sharma PK, Khandelwal SK. Effect of phosphorus and weed control on fenugreek (*Trigonella foenum-graecum* L.). Legume Research. 2006;29:304–7.

36. Birla L, Naruka IS, Shaktawat RPS, Ajnave SR. Integrated weed management in cumin. Indian Journal of Weed Science. 2016;48:102. https://doi.org/10.5958/0974-8164.2016.00027.7

37. Yadav RS, Sharma SK, Poonia BL, Dahama AK. Selectivity and phytotoxicity of oxadiargyl on cumin and weeds and its residual effect on succeeding mothbean and pearl millet. Indian Journal of Weed Science. 2015;66:83–5.