



RESEARCH ARTICLE

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

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## 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<sup>-1</sup> 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<sup>-1</sup> 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

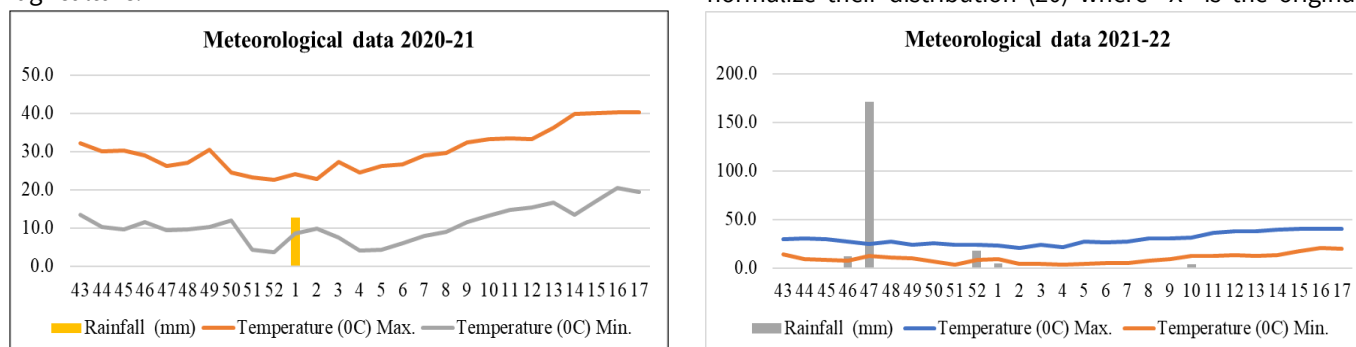
### Experimental site description and treatment details

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<sup>-1</sup>) and organic carbon content (0.56 %) along with high potassium content (465.55 kg ha<sup>-1</sup>). 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<sup>-1</sup>. Fertilization followed the recommended guidelines, applying 90 kg N ha<sup>-1</sup>, 40 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 20 kg K<sub>2</sub>O ha<sup>-1</sup>. 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<sup>-1</sup> PE (T<sub>1</sub>), pendimethalin 750 g ha<sup>-1</sup> PE *fb* HW at 40 DAS (T<sub>2</sub>), pendimethalin 750 g ha<sup>-1</sup> PE quizalofop ethyl 40 g ha<sup>-1</sup> PoE (T<sub>3</sub>), oxadiargyl 100 g ha<sup>-1</sup> PE (T<sub>4</sub>), oxadiargyl 75 g ha<sup>-1</sup> PE *fb* HW at 40 DAS (T<sub>5</sub>), oxadiargyl 75 g ha<sup>-1</sup> PE *fb* quizalofop ethyl 40 g ha<sup>-1</sup> PoE (T<sub>6</sub>), oxadiargyl 50 g ha<sup>-1</sup> PoE (T<sub>7</sub>), oxyfluorfen 100 g ha<sup>-1</sup> PE (T<sub>8</sub>), oxyfluorfen 75 g ha<sup>-1</sup> PE *fb* HW at 40 DAS (T<sub>9</sub>), oxyfluorfen 75 g ha<sup>-1</sup> PE *fb* quizalofop ethyl 40 g ha<sup>-1</sup> PoE (T<sub>10</sub>), IC *fb* HW at 20 & 40 DAS (T<sub>11</sub>), Oxadiargyl 50 g ha<sup>-1</sup> + propaquizafop 50 g ha<sup>-1</sup> PoE (T<sub>12</sub>) and weedy check (T<sub>13</sub>).

### 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 h 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 <sub>1</sub>  | Pendimethalin 1000 g ha <sup>-1</sup> PE                                              |
| T <sub>2</sub>  | Pendimethalin 750 g ha <sup>-1</sup> PE fb HW 40 DAS                                  |
| T <sub>3</sub>  | Pendimethalin 750 g ha <sup>-1</sup> PE fb quizalofop ethyl 40 g ha <sup>-1</sup> PoE |
| T <sub>4</sub>  | Oxadiargyl 100 g ha <sup>-1</sup> PE                                                  |
| T <sub>5</sub>  | Oxadiargyl 75 g ha <sup>-1</sup> PE fb HW 40 DAS                                      |
| T <sub>6</sub>  | Oxadiargyl 75 g ha <sup>-1</sup> PE fb quizalofop ethyl 40 g ha <sup>-1</sup> PoE     |
| T <sub>7</sub>  | Oxadiargyl 50 g ha <sup>-1</sup> PoE                                                  |
| T <sub>8</sub>  | Oxyfluorfen 100 g ha <sup>-1</sup> PE                                                 |
| T <sub>9</sub>  | Oxyfluorfen 75 g ha <sup>-1</sup> PE fb HW 40 DAS                                     |
| T <sub>10</sub> | Oxyfluorfen 75 g ha <sup>-1</sup> PE fb quizalofop ethyl 40 g ha <sup>-1</sup> PoE    |
| T <sub>11</sub> | IC fb HW at 20 & 40 DAS                                                               |
| T <sub>12</sub> | Oxadiargyl 50 g ha <sup>-1</sup> + propaquizafop 50 g ha <sup>-1</sup> PoE            |
| T <sub>13</sub> | Weedy check                                                                           |

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

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

### 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<sup>-1</sup>). 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 [ $\sqrt{(X + 0.5)}$ ] where "X" represents the original values.

## Results and Discussion

### Effect on weeds

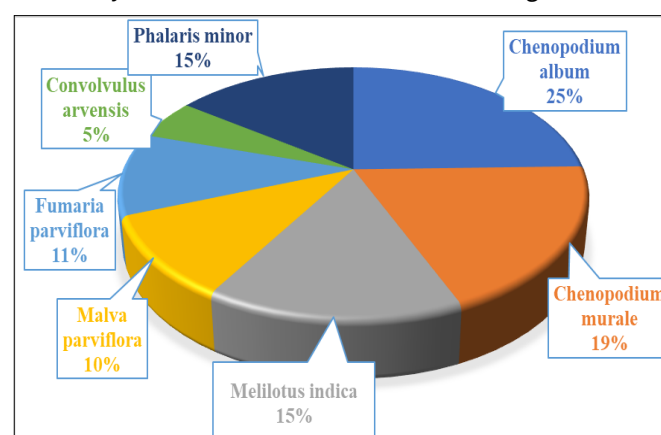
The experimental field was primarily infested with broadleaved weeds representing 84.99 % of the total weed population while grassy weeds comprised 14.99 % (Fig. 2). The broadleaved species included *Chenopodium album*, *Chenopodium murale*, *Melilotus indica*, *Malva parviflora*, *Fumaria parviflora* 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<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup>. 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<sup>-1</sup> 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

**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 <sup>-2</sup> ) |                           |                           |                             |                           |                            |                           |
|-----------------|-------------------------------------|---------------------------|---------------------------|-----------------------------|---------------------------|----------------------------|---------------------------|
|                 | <i>Chenopodium Album</i>            | <i>Chenopodium Murale</i> | <i>Fumaria parviflora</i> | <i>Convolvulus arvensis</i> | <i>Phalaris minor</i>     | <i>Melilotus indica</i>    | <i>Malva parviflora</i>   |
| T <sub>1</sub>  | 1.33(1.26) <sup>efg</sup>           | 1.47(1.67) <sup>cde</sup> | 1.64(2.20) <sup>b</sup>   | 1.23(1.03) <sup>g</sup>     | 1.59(2.03) <sup>bcd</sup> | 1.38(1.42) <sup>cde</sup>  | 1.30(1.19) <sup>bcd</sup> |
| T <sub>2</sub>  | 1.36(1.34) <sup>ef</sup>            | 1.53(1.86) <sup>cde</sup> | 1.74(2.53) <sup>b</sup>   | 1.33(1.28) <sup>ef</sup>    | 2.01(3.55) <sup>bcd</sup> | 1.48(1.69) <sup>cde</sup>  | 1.32(1.24) <sup>bcd</sup> |
| T <sub>3</sub>  | 1.64(2.20) <sup>c</sup>             | 1.69(2.35) <sup>bcd</sup> | 2.28(4.72) <sup>b</sup>   | 1.50(1.76) <sup>c</sup>     | 1.66(2.27) <sup>bcd</sup> | 1.89(3.06) <sup>bcd</sup>  | 1.65(2.23) <sup>bcd</sup> |
| T <sub>4</sub>  | 1.03(0.59) <sup>h</sup>             | 1.26(1.09) <sup>e</sup>   | 1.55(1.90) <sup>b</sup>   | 1.15(0.81) <sup>h</sup>     | 1.15(0.83) <sup>d</sup>   | 1.12(0.80) <sup>e</sup>    | 1.02(0.54) <sup>d</sup>   |
| T <sub>5</sub>  | 1.13(0.77) <sup>gh</sup>            | 1.41(1.48) <sup>de</sup>  | 1.64(2.20) <sup>b</sup>   | 1.24(1.03) <sup>g</sup>     | 1.49(1.73) <sup>bcd</sup> | 1.28(1.13) <sup>de</sup>   | 1.15(0.82) <sup>bcd</sup> |
| T <sub>6</sub>  | 1.61(2.10) <sup>cd</sup>            | 1.65(2.23) <sup>bcd</sup> | 2.25(4.58) <sup>b</sup>   | 1.45(1.60) <sup>cd</sup>    | 1.47(1.67) <sup>bcd</sup> | 1.58(2.00) <sup>bcde</sup> | 1.59(2.02) <sup>bcd</sup> |
| T <sub>7</sub>  | 1.18(0.88) <sup>fg</sup>            | 1.43(1.55) <sup>de</sup>  | 1.66(2.27) <sup>b</sup>   | 1.25(1.07) <sup>fg</sup>    | 1.95(3.28) <sup>bcd</sup> | 1.37(1.37) <sup>de</sup>   | 1.25(1.06) <sup>bcd</sup> |
| T <sub>8</sub>  | 1.36(1.36) <sup>ef</sup>            | 1.55(1.91) <sup>cde</sup> | 2.06(3.75) <sup>b</sup>   | 1.37(1.38) <sup>de</sup>    | 1.72(2.47) <sup>bcd</sup> | 1.49(1.73) <sup>cde</sup>  | 1.36(1.36) <sup>bcd</sup> |
| T <sub>9</sub>  | 1.39(1.44) <sup>de</sup>            | 1.58(1.98) <sup>cde</sup> | 2.10(3.93) <sup>b</sup>   | 1.38(1.42) <sup>de</sup>    | 2.05(3.69) <sup>bcd</sup> | 1.55(1.89) <sup>bcde</sup> | 1.53(1.83) <sup>bcd</sup> |
| T <sub>10</sub> | 2.06(3.76) <sup>b</sup>             | 1.83(2.86) <sup>bc</sup>  | 2.38(5.16) <sup>b</sup>   | 1.63(2.18) <sup>b</sup>     | 1.91(3.17) <sup>bc</sup>  | 1.96(3.32) <sup>bc</sup>   | 1.79(2.72) <sup>bc</sup>  |
| T <sub>11</sub> | 1.10(0.72) <sup>h</sup>             | 1.34(1.29) <sup>de</sup>  | 1.60(2.05) <sup>b</sup>   | 1.21(0.97) <sup>gh</sup>    | 1.38(1.40) <sup>cd</sup>  | 1.25(1.06) <sup>e</sup>    | 1.12(0.76) <sup>cd</sup>  |
| T <sub>12</sub> | 2.12(4.00) <sup>b</sup>             | 1.93(3.23) <sup>b</sup>   | 2.56(6.08) <sup>b</sup>   | 1.72(2.45) <sup>b</sup>     | 2.19(4.30) <sup>b</sup>   | 2.09(3.87) <sup>b</sup>    | 1.85(2.92) <sup>b</sup>   |
| T <sub>13</sub> | 4.90(23.52) <sup>a</sup>            | 4.33(18.23) <sup>a</sup>  | 3.27(10.18) <sup>a</sup>  | 2.34(4.97) <sup>a</sup>     | 3.85(14.34) <sup>a</sup>  | 3.85(14.35) <sup>a</sup>   | 3.24(10.02) <sup>a</sup>  |

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 <sup>-2</sup> ) |                           |                           |                             |                           |                           |                          |
|-----------------|--------------------------------------|---------------------------|---------------------------|-----------------------------|---------------------------|---------------------------|--------------------------|
|                 | <i>Chenopodium album</i>             | <i>Chenopodium murale</i> | <i>Fumaria parviflora</i> | <i>Convolvulus arvensis</i> | <i>Phalaris minor</i>     | <i>Melilotus indica</i>   | <i>Malva parviflora</i>  |
| T <sub>1</sub>  | 1.03(0.57) <sup>d</sup>              | 1.12(0.76) <sup>efg</sup> | 1.24(1.05) <sup>g</sup>   | 1.01(0.52) <sup>ef</sup>    | 1.23(1.00) <sup>fg</sup>  | 1.08(0.66) <sup>def</sup> | 1.22(1.01) <sup>bc</sup> |
| T <sub>2</sub>  | 1.05(0.61) <sup>d</sup>              | 1.16(0.85) <sup>def</sup> | 1.31(1.22) <sup>f</sup>   | 1.06(0.62) <sup>de</sup>    | 1.48(1.70) <sup>bcd</sup> | 1.15(0.83) <sup>def</sup> | 1.50(1.83) <sup>bc</sup> |
| T <sub>3</sub>  | 1.22(0.99) <sup>c</sup>              | 1.26(1.08) <sup>c</sup>   | 1.64(2.18) <sup>d</sup>   | 1.17(0.88) <sup>c</sup>     | 1.25(1.07) <sup>efg</sup> | 1.38(1.42) <sup>bc</sup>  | 1.92(3.33) <sup>b</sup>  |
| T <sub>4</sub>  | 0.87(0.27) <sup>f</sup>              | 1.00(0.49) <sup>h</sup>   | 1.18(0.89) <sup>h</sup>   | 0.95(0.41) <sup>f</sup>     | 0.96(0.42) <sup>h</sup>   | 0.95(0.41) <sup>f</sup>   | 1.00(0.50) <sup>c</sup>  |
| T <sub>5</sub>  | 0.92(0.35) <sup>ef</sup>             | 1.08(0.67) <sup>fgh</sup> | 1.25(1.05) <sup>g</sup>   | 1.01(0.52) <sup>ef</sup>    | 1.18(0.88) <sup>fg</sup>  | 1.05(0.59) <sup>def</sup> | 1.06(0.63) <sup>c</sup>  |
| T <sub>6</sub>  | 1.20(0.95) <sup>c</sup>              | 1.24(1.05) <sup>cd</sup>  | 1.63(2.16) <sup>d</sup>   | 1.13(0.77) <sup>cd</sup>    | 1.16(0.84) <sup>fg</sup>  | 1.25(1.05) <sup>cd</sup>  | 1.56(1.95) <sup>bc</sup> |
| T <sub>7</sub>  | 0.95(0.40) <sup>e</sup>              | 1.10(0.71) <sup>efg</sup> | 1.26(1.10) <sup>g</sup>   | 1.03(0.56) <sup>def</sup>   | 1.42(1.51) <sup>cde</sup> | 1.08(0.67) <sup>def</sup> | 1.37(1.46) <sup>bc</sup> |
| T <sub>8</sub>  | 1.06(0.62) <sup>d</sup>              | 1.17(0.87) <sup>cde</sup> | 1.49(1.73) <sup>e</sup>   | 1.12(0.76) <sup>cd</sup>    | 1.32(1.25) <sup>def</sup> | 1.17(0.87) <sup>cde</sup> | 1.29(1.33) <sup>bc</sup> |
| T <sub>9</sub>  | 1.07(0.65) <sup>d</sup>              | 1.19(0.91) <sup>fde</sup> | 1.53(1.83) <sup>e</sup>   | 1.09(0.69) <sup>cde</sup>   | 1.53(1.86) <sup>bc</sup>  | 1.20(0.93) <sup>cde</sup> | 1.70(2.42) <sup>bc</sup> |
| T <sub>10</sub> | 1.50(1.77) <sup>b</sup>              | 1.36(1.34) <sup>b</sup>   | 1.75(2.56) <sup>c</sup>   | 1.28(1.16) <sup>b</sup>     | 1.45(1.61) <sup>cd</sup>  | 1.47(1.65) <sup>b</sup>   | 1.66(2.25) <sup>bc</sup> |
| T <sub>11</sub> | 0.91(0.33) <sup>ef</sup>             | 1.04(0.59) <sup>gh</sup>  | 1.23(1.02) <sup>g</sup>   | 1.00(0.51) <sup>ef</sup>    | 1.10(0.71) <sup>gh</sup>  | 1.00(0.50) <sup>ef</sup>  | 1.07(0.64) <sup>c</sup>  |
| T <sub>12</sub> | 1.52(1.81) <sup>b</sup>              | 1.40(1.47) <sup>b</sup>   | 1.84(2.88) <sup>b</sup>   | 1.32(1.24) <sup>b</sup>     | 1.63(2.17) <sup>b</sup>   | 1.52(1.80) <sup>b</sup>   | 1.71(2.43) <sup>bc</sup> |
| T <sub>13</sub> | 3.36(10.77) <sup>a</sup>             | 3.00(8.50) <sup>a</sup>   | 2.27(4.65) <sup>a</sup>   | 1.73(2.51) <sup>a</sup>     | 2.70(6.78) <sup>a</sup>   | 2.82(7.46) <sup>a</sup>   | 2.99(8.46) <sup>a</sup>  |

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 <sup>-2</sup> ) |                          |                          | Weed dry matter (g m <sup>-2</sup> ) |                           |                           | Weed control efficiency (%) |             |       |
|-----------------|---------------------------------|--------------------------|--------------------------|--------------------------------------|---------------------------|---------------------------|-----------------------------|-------------|-------|
|                 | Grassy                          | Broadleaved              | Total                    | Grassy                               | Broadleaved               | Total                     | Grassy                      | Broadleaved | Total |
| T <sub>1</sub>  | 1.59(2.03) <sup>de</sup>        | 3.04(8.77) <sup>gh</sup> | 3.36(10.80) <sup>g</sup> | 1.23(1.00) <sup>fg</sup>             | 2.25(4.57) <sup>fg</sup>  | 2.46(5.58) <sup>gh</sup>  | 85.19                       | 89.21       | 88.65 |
| T <sub>2</sub>  | 2.01(3.55) <sup>c</sup>         | 3.23(9.93) <sup>g</sup>  | 3.74(13.48) <sup>f</sup> | 1.48(1.70) <sup>bcd</sup>            | 2.54(5.96) <sup>ef</sup>  | 2.85(7.66) <sup>def</sup> | 74.88                       | 85.94       | 84.41 |
| T <sub>3</sub>  | 1.66(2.27) <sup>d</sup>         | 4.10(16.31) <sup>d</sup> | 4.37(18.58) <sup>d</sup> | 1.25(1.07) <sup>efg</sup>            | 3.21(9.88) <sup>bcd</sup> | 3.37(10.94) <sup>bc</sup> | 84.29                       | 76.69       | 77.74 |
| T <sub>4</sub>  | 1.15(0.83) <sup>g</sup>         | 2.49(5.73) <sup>k</sup>  | 2.65(6.56) <sup>i</sup>  | 0.96(0.42) <sup>h</sup>              | 1.86(2.97) <sup>g</sup>   | 1.97(3.40) <sup>i</sup>   | 93.78                       | 92.98       | 93.09 |
| T <sub>5</sub>  | 1.49(1.73) <sup>ef</sup>        | 2.82(7.45) <sup>ji</sup> | 3.11(9.17) <sup>h</sup>  | 1.18(0.88) <sup>fg</sup>             | 2.08(3.81) <sup>g</sup>   | 2.28(4.70) <sup>ghi</sup> | 86.95                       | 90.99       | 90.44 |
| T <sub>6</sub>  | 1.47(1.67) <sup>ef</sup>        | 3.88(14.53) <sup>e</sup> | 4.09(16.20) <sup>e</sup> | 1.16(0.84) <sup>fg</sup>             | 2.90(7.93) <sup>cde</sup> | 3.04(8.78) <sup>cde</sup> | 87.58                       | 81.27       | 82.14 |
| T <sub>7</sub>  | 1.95(3.28) <sup>c</sup>         | 2.95(8.20) <sup>hi</sup> | 3.46(11.49) <sup>g</sup> | 1.42(1.51) <sup>cde</sup>            | 2.32(4.90) <sup>fg</sup>  | 2.63(6.42) <sup>efg</sup> | 77.70                       | 88.42       | 86.94 |
| T <sub>8</sub>  | 1.72(2.47) <sup>d</sup>         | 3.46(11.50) <sup>f</sup> | 3.80(13.97) <sup>f</sup> | 1.32(1.25) <sup>def</sup>            | 2.58(6.18) <sup>ef</sup>  | 2.81(7.43) <sup>def</sup> | 81.57                       | 85.42       | 84.88 |
| T <sub>9</sub>  | 2.05(3.69) <sup>bc</sup>        | 3.61(12.50) <sup>f</sup> | 4.09(16.19) <sup>e</sup> | 1.53(1.86) <sup>bc</sup>             | 2.81(7.42) <sup>de</sup>  | 3.13(9.28) <sup>cd</sup>  | 72.59                       | 82.47       | 81.11 |
| T <sub>10</sub> | 1.91(3.17) <sup>c</sup>         | 4.53(20.01) <sup>c</sup> | 4.87(23.18) <sup>c</sup> | 1.45(1.61) <sup>cd</sup>             | 3.35(10.73) <sup>bc</sup> | 3.58(12.34) <sup>b</sup>  | 76.26                       | 74.68       | 74.89 |
| T <sub>11</sub> | 1.38(1.40) <sup>f</sup>         | 2.71(6.85) <sup>j</sup>  | 2.96(8.24) <sup>h</sup>  | 1.10(0.71) <sup>gh</sup>             | 2.02(3.58) <sup>g</sup>   | 2.19(4.29) <sup>hi</sup>  | 89.53                       | 91.54       | 91.26 |
| T <sub>12</sub> | 2.19(4.30) <sup>b</sup>         | 4.80(22.56) <sup>b</sup> | 5.23(26.85) <sup>b</sup> | 1.63(2.17) <sup>b</sup>              | 3.48(11.64) <sup>b</sup>  | 3.78(13.81) <sup>b</sup>  | 67.99                       | 72.52       | 71.90 |
| T <sub>13</sub> | 3.85(14.4) <sup>a</sup>         | 9.04(81.27) <sup>a</sup> | 9.80(95.61) <sup>a</sup> | 2.70(6.78) <sup>a</sup>              | 6.55(42.36) <sup>a</sup>  | 7.05(49.14) <sup>a</sup>  | 0.00                        | 0.00        | 0.00  |

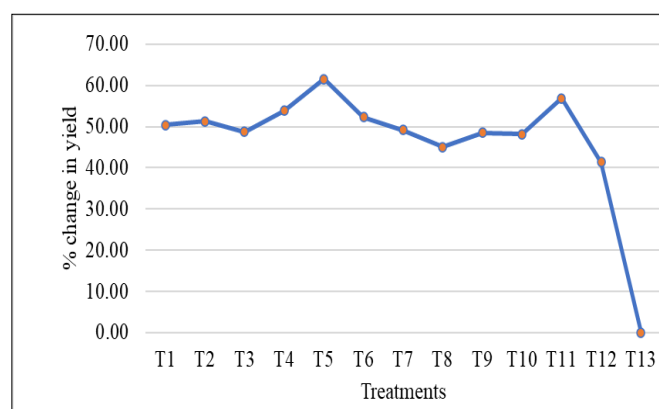
Data subjected to  $\sqrt{x + 0.5}$  transformation and figures in parenthesis are original weed count and weed dry matter per sq. m

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

| Treatments      | Plant height (cm)    | Plant dry matter (g) | Seed yield plant <sup>-1</sup> (g) | Test weight (g)      | Biological yield (q ha <sup>-1</sup> ) |
|-----------------|----------------------|----------------------|------------------------------------|----------------------|----------------------------------------|
|                 | 30 DAS               |                      |                                    |                      |                                        |
| T <sub>1</sub>  | 38.37 <sup>bc</sup>  | 7.14 <sup>abcd</sup> | 3.29 <sup>bcde</sup>               | 3.77 <sup>abcd</sup> | 27.35 <sup>cd</sup>                    |
| T <sub>2</sub>  | 37.57 <sup>bc</sup>  | 6.43 <sup>cd</sup>   | 3.45 <sup>abcd</sup>               | 3.85 <sup>abcd</sup> | 27.82 <sup>cd</sup>                    |
| T <sub>3</sub>  | 35.76 <sup>c</sup>   | 7.04 <sup>abcd</sup> | 3.05 <sup>cde</sup>                | 3.63 <sup>bcde</sup> | 26.44 <sup>cde</sup>                   |
| T <sub>4</sub>  | 44.25 <sup>a</sup>   | 8.22 <sup>a</sup>    | 3.82 <sup>ab</sup>                 | 4.20 <sup>abc</sup>  | 29.41 <sup>bc</sup>                    |
| T <sub>5</sub>  | 39.47 <sup>abc</sup> | 7.10 <sup>abcd</sup> | 3.98 <sup>a</sup>                  | 4.39 <sup>a</sup>    | 35.3 <sup>a</sup>                      |
| T <sub>6</sub>  | 39.68 <sup>abc</sup> | 7.42 <sup>abc</sup>  | 3.59 <sup>abc</sup>                | 3.94 <sup>abcd</sup> | 28.39 <sup>bc</sup>                    |
| T <sub>7</sub>  | 36.07 <sup>c</sup>   | 6.93 <sup>abcd</sup> | 3.08 <sup>cde</sup>                | 3.71 <sup>bcde</sup> | 26.65 <sup>cd</sup>                    |
| T <sub>8</sub>  | 35.80 <sup>c</sup>   | 6.44 <sup>cd</sup>   | 2.88 <sup>de</sup>                 | 3.48 <sup>de</sup>   | 24.7 <sup>de</sup>                     |
| T <sub>9</sub>  | 34.82 <sup>c</sup>   | 6.79 <sup>bcd</sup>  | 2.98 <sup>de</sup>                 | 3.54 <sup>cde</sup>  | 26.31 <sup>cde</sup>                   |
| T <sub>10</sub> | 36.74 <sup>c</sup>   | 6.73 <sup>bcd</sup>  | 2.93 <sup>de</sup>                 | 3.51 <sup>de</sup>   | 26.16 <sup>cde</sup>                   |
| T <sub>11</sub> | 42.73 <sup>ab</sup>  | 7.76 <sup>ab</sup>   | 3.88 <sup>ab</sup>                 | 4.25 <sup>ab</sup>   | 31.42 <sup>b</sup>                     |
| T <sub>12</sub> | 34.92 <sup>c</sup>   | 6.29 <sup>cd</sup>   | 2.87 <sup>de</sup>                 | 3.43 <sup>de</sup>   | 23.14 <sup>e</sup>                     |
| T <sub>13</sub> | 34.27 <sup>c</sup>   | 6.09 <sup>d</sup>    | 2.75 <sup>e</sup>                  | 3.05 <sup>e</sup>    | 13.56 <sup>f</sup>                     |

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

development resulting in overall better plant performance. Further, enhanced yield attributes namely test weight and seed yield per plant were observed with the application of oxadiargyl @ 75 g ha<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup> PE. This was followed by treatment T<sub>11</sub> 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<sub>12</sub>) 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

**Fig. 3.** Per cent change in biological yield as compared to weedy check (T<sub>13</sub>).

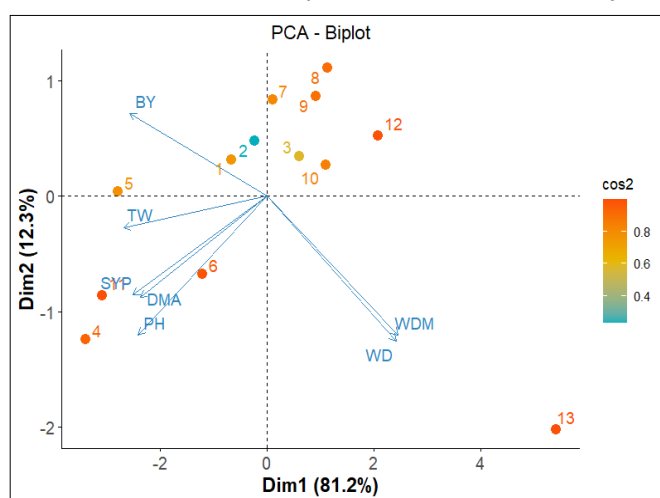
and subsequently the seed yield of dill (24, 32-35).

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-



**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)

related traits (BY, TW) suggests the importance of effective weed control in better growth and development of crops.

## 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<sup>-1</sup>, 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<sup>-1</sup> 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

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