



RESEARCH ARTICLE

Effect of different weed management practices on organically grown cotton

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Abstract

Weeds pose a significant challenge in cotton cultivation by competing with the crop for essential resources such as sunlight, water and nutrients, ultimately leading to reduced yield and fibre quality if not effectively controlled. Although chemical herbicides have been widely used for weed management, rising concerns over herbicide resistance, environmental impacts and the need for sustainable agriculture have encouraged the adoption of organic alternatives. Among these, mulching has been recognised as an effective practice for weed suppression while improving soil health and reducing dependence on synthetic chemicals. A field study was conducted during the kharif seasons from 2020–2024 at the Centre for Organic Agriculture Research and Training, Department of Agronomy, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, to evaluate the effects of different weed management practices in organically grown cotton. The results indicated that crop growth parameters including plant height, leaf area per plant, number of sympodial branches per plant and dry matter accumulation per plant along with yield attributes such as number of picked bolls per plant, boll weight per plant and seed cotton yield per plant were significantly higher under the stale seedbed method combined with twice hand weeding, showing performance comparable to that of straw mulch. This treatment also recorded lower weed density and weed dry weight, along with higher weed control efficiency. Economic analysis revealed that stale seedbed with hand weeding produced higher gross returns, whereas straw mulch was more profitable with better net returns and benefit-cost ratio, indicating its suitability as a sustainable weed management option for organic cotton.

Keywords: organic cotton; seed cotton yield; stale seedbed; sustainable farming; weed control efficiency; weed management

Introduction

Cotton (*Gossypium hirsutum* L.) plays a vital role in agriculture, especially in the semi-arid areas of India. Often referred to as the "king" of fibre crops and popularly known as "white gold," it stands among the most valuable cash crops globally. Cotton seed contains about 15–20 % oil and is used as a vegetable oil and in soap industries. Nearly one-third of India's export earnings are from the textile sector, of which cotton alone constitutes almost 70 % of the raw material. In India, the area under organic cultivation is 4.73 million ha. Madhya Pradesh stands out as the leading state, accounting for 1.5 million ha (approximately 27 %) of India's organic farming area, followed by Maharashtra and Gujarat. India ranked fifth globally in terms of organic agricultural area in 2021, fell to sixth in 2023 and currently ranks first in terms of the total number of organic producers worldwide (1). The organic cotton market in India was valued at USD 51.0 million in 2024 and is projected to reach USD 955.9 million by 2033, growing at a compound annual growth rate (CAGR) of 38.5 % (2).

Organic cotton has provided significant price premiums for

growers willing to meet the many challenges inherent in its production without the aid of conventional pesticides and commercial fertilisers. Cotton, a wide-spaced and relatively slow-growing crop during its initial growth stages, experiences severe weed competition, causing a reduction in seed cotton yields by up to 69 % (3). The increasing cost of manual weeding and the timely unavailability of labour have promoted reliance on herbicides for weed control in cotton. However, the widespread use of agrochemicals has resulted in potential environmental and health concerns. In addition, herbicide application may lead to the dominance of certain weed species through the development of herbicide resistance.

Cotton hybrids are grown at wide inter-row spacing, allowing the possibility of intercropping between rows. The associated benefits include weed suppression, higher seed cotton yield and improved profitability. It has been suggested that intercrops, when cut and left as mulch, return crop residues to the soil and improve soil quality. Practicing mulching for weed management provides numerous benefits, including weed suppression, reduced competition for resources, decreased

herbicide uses and improved plant growth and development. The principle of flushing out germinal weed seeds before cropping forms the basis of the stale or false seedbed technique, in which sowing is delayed after tillage and weeds that emerge are then destroyed with minor soil disturbance before crop planting (4). Considering these aspects, the present study was undertaken to evaluate the effect of various weed management practices on weed control efficiency and seed cotton yield.

Materials and Methods

Site description

A field experiment was conducted at certified organic plot number 66, Centre for Organic Agriculture Research and Training field, Department of Agronomy, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, under the All India Coordinated Research Project (AICRP) on Weed Management, during the kharif seasons from 2020–2024 at 22°42' N latitude and 77°02' E longitude, at an altitude of 307.42 m above mean sea level. The experimental site was certified organic under NPOP standards by Vedic Registration Firm, Hyderabad. The soil of the experimental plot was clayey in texture, low in available nitrogen (179 kg ha⁻¹), medium in available phosphorus (17.4 kg ha⁻¹) and high in available K (333 kg ha⁻¹), with a pH of 7.78.

Field preparation and sowing

The experimental field was prepared thoroughly with a tractor-mounted disc plough, followed by a tractor-drawn harrow and cultivator to achieve optimum tilth. The cotton seeds (var. PDKV Shubhra) were treated with bijamrut at 10 mL kg⁻¹ seed and sown during June as a rainfed crop at 60 × 30 cm spacing using the dibbling method. The crop was supplied with 40:20:20 kg N, P₂O₅ and K₂O ha⁻¹ with the application of compost at 3t ha⁻¹ and vermicompost at 5t ha⁻¹. Gap filling and thinning were undertaken to maintain an optimum plant population.

Treatment details

The experiment was laid out in a randomized block design (RBD) with seven treatments replicated thrice in a plot size of 11.2 m × 7.2 m. The seven treatments included stale seedbed + hand weeding at 20 and 40 days after sowing (DAS), intercrop green gram, sunhemp mulch, weed mulch at 30 DAS, straw mulch

at 20 DAS, farmer practices and weedy check. Farmer practices included 2 hoeings and 2 hand weeding operations performed at 20 DAS and 40 DAS. In the stale seedbed plots, 1 irrigation was applied 15 days prior to sowing to allow the germination of weeds and the first flush of emerged weed seedlings was removed by shallow soil disturbance (up to 2 cm) at the time of crop sowing (5). Sunhemp was sown between cotton rows and after 40 DAS the crop was cut and uniformly spread over the soil surface as mulch. Green gram was sown between crop rows and mulched on the soil at 50 DAS. Soybean straw mulch at 5 t ha⁻¹ was spread between 2 rows of cotton after 20 DAS. After every weeding, *in situ* weed mulching was practiced. Pest management was carried out through integrated pest management (IPM) practices including installation of sticky traps for sucking pest and application of Dashparni Ark.

Weather parameters

Akola lies near the Tropic of Cancer and experiences high temperatures during summer, particularly in May. The average annual precipitation over the last 30 years is 811.9 mm, with most rainfall occurring during the monsoon season between June and September. The total rainfall received during the kharif cotton growing period was 776.1 mm (2020), 1084 mm (2021), 1162 mm (2022), 694.5 mm (2023) and 740.4 mm (2024). Mean monthly maximum and minimum temperatures ranged between 29.6–35.3 °C and 12.5–24.6 °C (2020), 28.4–34.5 °C and 12.8–24 °C (2021), 29.2–37 °C and 10.9–24.4 °C (2022), 27.3–38.8 °C and 12.6–24.5 °C (2023) and 29.2–37.5 °C and 10.2–22 °C (2024) (Fig. 1).

Biometric observations

Plant height (cm), leaf area (dm²), number of sympodial branches per plant, dry matter accumulation per plant (g) were recorded from 5 randomly selected plants. The number of picked bolls per plant, boll weight per plant and seed cotton yield per plant were recorded after the first picking of cotton. Data on weed density and weed dry matter were recorded at 30 and 60 DAS using a 1 × 1 m quadrat placed randomly within the plot. Weeds were counted species wise and removed for biomass estimation. The weeds were first air dried and then oven-dried at 65 °C until constant dry weight was obtained. Weed control efficiency (WCE, %) of treatment was calculated using the following formula (6):

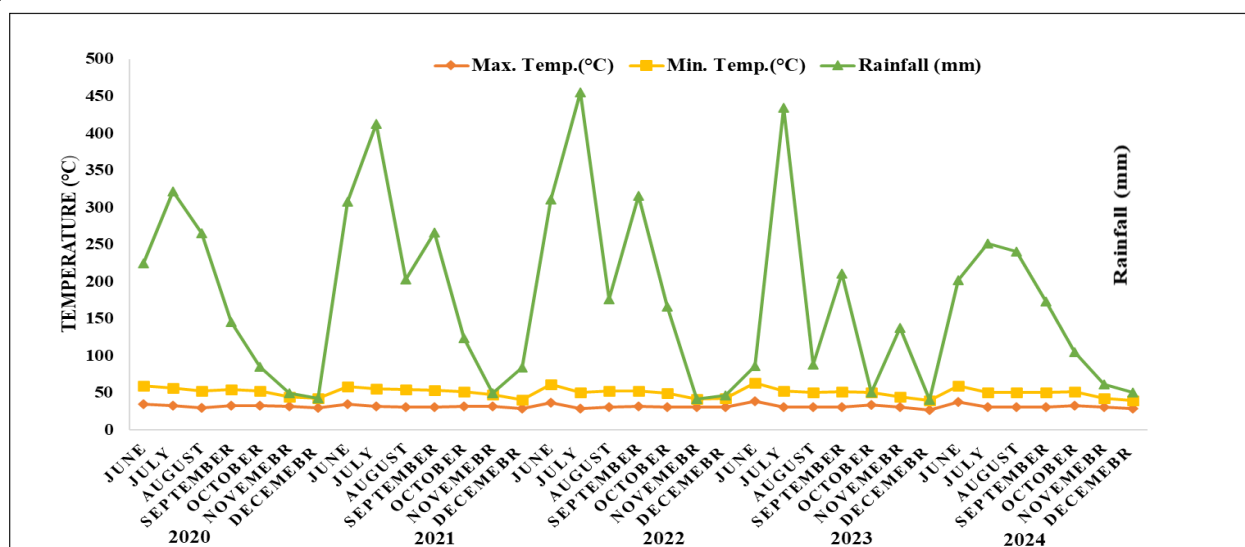


Fig. 1. Monthly maximum, minimum temperature and rainfall during the crop growth period from 2020–2024.

$$\text{WCE (\%)} = \frac{\text{DWC} - \text{DWT}}{\text{DWC}} \times 100$$

Where,

WCE = weed control efficiency; DWC = weed dry weight in control plot; DWT = weed dry weight in treated plot.

Statistical analysis

Data from 5 kharif seasons (2020–2024) were analysed using OPSTAT software (7). Since error variances were homogeneous, the data were analysed for combined means using analysis of variance (ANOVA) and treatment means were compared using the least significant difference (LSD) test at 5 % probability level. Data on weed density and weed dry weight exhibited high variability; therefore, square root transformation was applied prior to ANOVA to improve the validity of statistical interpretation.

Results

The analysis of weed data obtained from the experiment showed varied responses to different weed management practices (Table 1).

Weed flora

Weed flora of the experimental field consisted of broad-leaved weeds (BLW), including *Parthenium hysterophorus* L., *Trianthema portulacastrum* L., *Alternanthera sessilis* (L.) R.Br. ex DC., *Digeria arvensis* Forssk. and *Phyllanthus niruri* L.; grasses such as *Cynodon dactylon* (L.) Pers., *Commelina benghalensis* L., *Echinochloa crusgalli* (L.) P. Beauv and *Dinebra retroflexa* (Vahl) Panz; and sedges such as *Cyperus rotundus*.

Weed density and weed dry weight

The weed density (no. m⁻²) at 30 DAS was found to be highest in the weedy check treatment (55.90), which was statistically at par with sunhemp mulch (37.64). In contrast, farmer practices (28.89) recorded the lowest weed density and were statistically comparable with straw mulch (29.28). The treatment stale seedbed with twice hand weeding (30.42) recorded a significantly lower weed density compared to the weedy check and intercrop mulch; however, it differed significantly from weed mulch treatments. At 60 DAS, the lowest weed density was observed under farmer practices (25.60), which was statistically comparable with stale seedbed (34.06).

Higher weed dry matter (g m⁻²) was observed in the weedy check (36.13), followed by sunhemp mulch (12.97) at 30 DAS. The lowest weed dry weight (g m⁻²) was recorded under stale seedbed with twice hand weeding (8.14), which was statistically at par with farmer practices (9.23) at 30 DAS. Furthermore, at 60 DAS, the lowest weed dry weight was recorded under farmer practices (13.36), followed by stale seed bed with twice hand weeding (13.76).

Weed control efficiency

At 30 and 60 DAS, significantly higher weed control efficiency was recorded in stale seedbed with twice hand weeding (77.47 and 69.17, respectively), followed by straw mulch (70.00 and 68.81, respectively). The lowest weed control efficiency was observed in the weedy check.

Growth and yield parameters

Different weed management practices significantly influenced cotton growth and yield parameters (Table 2). The highest plant height (61.3 cm) was recorded under t intercrop green gram mulch, which was statistically at par with weed mulch. The highest number of sympodial branches (15.09) was recorded under straw mulch, which was at par with weed mulch and sunhemp mulch. Farmer practices recorded the highest leaf area per plant and the maximum dry matter accumulation per plant (72.38 g) was also observed under farmer practices, followed by stale seedbed with twice hand weeding at harvest. The highest number of picked bolls per plant (11.17) was recorded under farmers practices, followed by stale seedbed with twice hand weeding and straw mulch. Boll weight per plant was not significantly influenced by the treatments. Farmers practices recorded the highest seed cotton yield per plant (26.8 g), followed by stale seedbed with twice hand weeding twice and straw mulch.

Seed cotton yield and economics

Seed cotton yield was significantly influenced by weed management practices (Table 3). The highest seed cotton yield (1512 kg ha⁻¹) was recorded under farmer practices, which was statistically at par with stale seedbed with twice hand weeding (1412 kg ha⁻¹). However, stale seed bed with twice hand weeding was closely followed by straw mulch (Fig. 2). The highest gross monetary returns (₹92734 ha⁻¹) were recorded under farmer practices, followed by stale seed bed with twice hand weeding (₹86537 ha⁻¹). However, net monetary returns under farmer practices, stale seed bed with twice

Table 1. Effect of weed management practices on weed density, dry weight and control efficiency in cotton

Treatment	Weed density (no. m ⁻²)		Weed dry weight (g m ⁻²)		Weed control efficiency (%)	
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
Stale seedbed + Hand weeding (20 & 40 DAS)	5.54 (30.42)	5.87 (34.06)	2.94 (8.14)	3.78 (13.76)	77.47	69.17
Intercrop Greengram	6.02 (35.82)	6.91 (47.67)	3.64 (12.78)	4.40 (18.85)	64.63	57.76
Sunhemp mulch	6.17 (37.64)	7.08 (49.79)	3.67 (12.97)	4.27 (17.81)	64.10	60.09
Weed mulch	6.10 (36.79)	7.45 (55.31)	3.47 (11.56)	4.23 (17.40)	68.00	61.01
Straw mulch	5.43 (29.28)	6.40 (40.93)	3.37 (10.84)	3.80 (13.92)	70.00	68.81
Farmer practices	5.42 (28.89)	5.09 (25.60)	3.12 (9.23)	3.72 (13.36)	74.45	70.06
Weedy check	7.50 (55.90)	8.44 (70.87)	5.98 (36.13)	6.68 (44.63)	0.00	0.00
SEm (±)	0.04	0.04	0.05	0.06	--	--
CD at 5 %	0.12	0.13	0.14	0.18	--	--

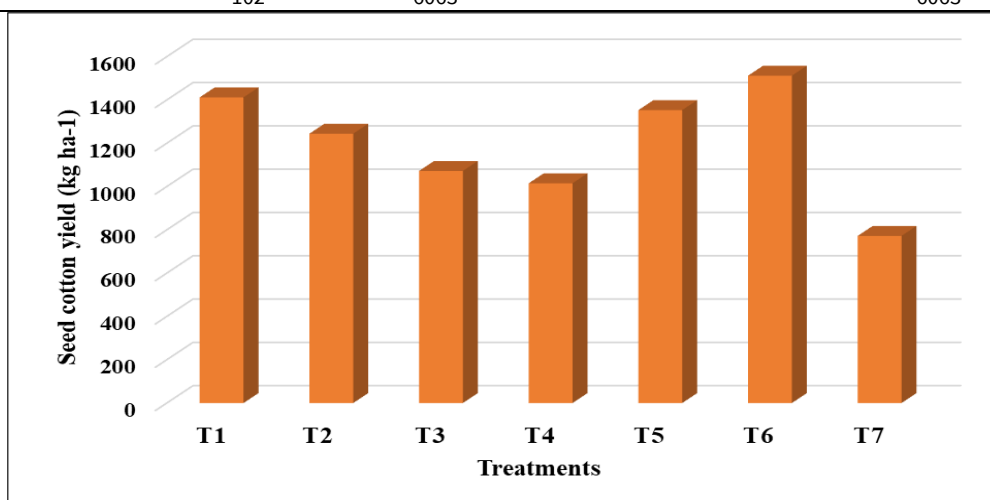
*Original values are given in parenthesis, which were transformed to $\sqrt{x} + 0.5$.

Table 2. Growth and yield parameters of cotton as influenced by weed management practices

Treatment	Plant height (cm)	Dry matter per plant at harvest (g)	Symptodial ranches per plant at harvest	Leaf area per plant (dm ²)	No. of picked bolls per plant	Boll weight per plant (g)	Seed cotton yield per plant (g)
Stale seedbed + Hand weeding (20 & 40 DAS)	58.33	71.11	13.64	71.24	10.28	2.30	25.23
Intercrop Greengram	61.3	69.82	13.21	70.64	8.93	2.17	21.17
Sunhemp mulch	59.92	69.31	14.42	70.14	8.79	1.96	18.94
Weed mulch	60.66	68.97	14.81	69.64	8.1	1.99	17.7
Straw mulch	59.27	70.53	15.09	70.84	10.08	2.12	23.83
Farmer practices	57.75	72.38	10.79	71.94	11.17	2.20	26.8
Weedy check	44.51	66.88	10.45	66.04	7.07	1.76	13.72
SEm (±)	3.41	0.97	0.49	1.64	0.12	0.04	0.36
CD at 5 %	10.3	2.96	1.48	4.91	0.34	NS	1.09

Table 3. Seed cotton yield and economics of cotton as influenced by weed management practices (pooled mean of 5 years)

Treatment	SCY (kg ha ⁻¹)	GMR (₹ ha ⁻¹)	Cost of cultivation (₹ ha ⁻¹)	NMR (₹ ha ⁻¹)	B:C
Stale seedbed + Hand weeding (20 & 40 DAS)	1412	86537	43055	43482	2.01
Intercrop Greengram	1244	76001	38375	37626	1.98
Sunhemp mulch	1072	64658	35825	28833	1.80
Weed mulch	1015	61128	35275	25853	1.73
Straw mulch	1353	82409	37475	44934	2.19
Farmer practices	1512	92734	47224	45510	1.96
Weedy check	772	47586	31027	16559	1.53
SEm (±)	34	2022	--	2022	--
CD at 5 %	102	6063	--	6063	--

**Fig. 2.** Seed cotton yield as influenced by weed management practices. T₁: stale seedbed + hand weeding (20 & 40 DAS); T₂: intercrop Greengram; T₃: sunhemp mulch; T₄: weed mulch; T₅: straw mulch; T₆: farmer practices; T₇: weedy check.

hand weeding and straw mulch did not differ significantly. The highest benefit:cost (B:C) ratio was recorded under straw mulch applied at 20 DAS.

Quality studies

Data on quality parameters, namely ginning percentage, lint index and fibre quality, were not significantly influenced by the treatments (Table 4). The highest ginning percentage was recorded under farmer practice (35.76), which was comparable with all live and

organic mulching treatments.

The data on fibre quality parameters, including 2.5 % staple length, micronaire value and earliness index, as influenced by different treatments, are presented in Table 4. The treatments did not significantly influence fibre quality parameters. However, numerically higher values of fibre quality parameters were observed under straw mulch.

Table 4. Fibre properties as influenced by weed management practices

Treatment	Ginning %	lint index	Fibre properties		
			2.5 % staple length (mm)	Micronaire value (10 ⁻⁶ g inch ⁻¹)	Earliness index
Stale seedbed + Hand weeding (20 & 40 DAS)	35.31	4.78	26.73	4.02	0.75
Intercrop Greengram	35.29	4.76	26.70	4.02	0.72
Sunhemp mulch	35.34	4.80	26.31	4.05	0.75
Weed mulch	35.37	4.84	26.60	4.05	0.74
Straw mulch	35.42	4.87	27.09	4.08	0.76
Farmer practices	35.76	4.64	26.24	4.01	0.72
Weedy check	34.23	4.52	25.11	3.94	0.71
SEm (±)	1.13	0.15	1.25	0.13	0.03
CD at 5 %	NS	NS	NS	NS	NS

Chemical studies

The chemical properties of soil play a crucial role in regulating nutrient availability and supporting plant growth. Parameters such as soil pH, electrical conductivity (EC) and organic carbon content directly influence nutrient dynamics and their uptake by crops. The data presented in Table 5 reflect the impact of different treatments on these soil chemical characteristics, highlighting their significance in sustaining soil fertility and effective nutrient management.

Soil pH significantly influences nutrient availability, soil structure and plant growth by affecting organic matter breakdown, cation exchange capacity and nutrient solubility. A decrease in soil pH was observed with mulch application. The electrical conductivity (EC) of the soil was not significantly influenced by the treatments. However, the lowest EC (0.27 dS m^{-1}) was recorded under weed mulch, whereas the highest EC (0.32 dS m^{-1}) was observed under farmer practices and intercrop mulch. The highest organic carbon content (0.56 %) was recorded in the sunhemp mulch, followed by straw mulch (0.55 %). The highest NPK uptake (kg ha^{-1}) was recorded under stale seedbed with hand weeding at 20 and 40 DAS, which was statistically at par with sunhemp mulch.

Physical properties

Bulk density is the most commonly used parameter to assess soil compaction. Soil swelling is associated with a decrease in bulk density and vice versa. Soil texture and moisture content are key factors influencing compaction. Vertisols are highly compressible soils, in which the weight of the topsoil compacts the subsoil, thereby significantly influencing the degree of compaction. At the beginning of the field investigation, the bulk density was 1.34 Mg m^{-3} . After the harvest of each cropping cycle, a decrease in bulk density was observed. However, no significant differences were found among the treatments. Numerically, higher bulk density was recorded under farmers' practice, whereas lower values were observed under different mulch treatments.

Soil biological indicator

Weed management practices significantly affected dehydrogenase activity (Table 6). A numerically higher value was observed under the application of sunhemp mulch ($52 \mu\text{g TPF g}^{-1} 24 \text{ hr}^{-1}$), which was on par with straw mulch, followed by intercrop mulch. The application of straw mulch resulted in higher soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN). These were closely followed by stale seedbed with twice hand weeding and sunhemp mulch; however, the differences were not significant and all treatments were on par during the field experiment. The highest earthworm population was observed under sunhemp mulch; however, it did not differ significantly from the other treatments.

Discussion

The stale seedbed technique with twice hand weeding recorded significantly lower weed dry weight, primarily due to the reduction of the weed seed bank in the shallow soil layer and was statistically on par with farmer practices, followed by straw mulch (8, 9). The favourable environment created for crop growth helped suppress weeds due to the beneficial effects of mulch, including moisture conservation, regulation of soil temperature and addition of organic matter to the soil. Similar findings were reported by previous studies (10–13).

The highest number of sympodial branches was recorded under straw mulch, followed by weed and sunhemp mulches. Maximum dry matter per plant was observed under farmer practices, with the stale seedbed with twice hand weeding treatment showing similar results. This may be attributed to the effectiveness of manual hoeing in reducing weed density, thereby enhancing dry matter accumulation. These results are consistent with previous reports (11, 14).

The substantial increase in the number of picked bolls per plant under stale seedbed and straw mulch treatments may be attributed to improvements in various growth attributes, viz. plant

Table 5. Soil physical and chemical properties after harvest as influenced by weed management practices

Treatment	Chemical properties			Nutrient uptake (kg ha^{-1})			Physical properties
	Soil pH	EC (dS m^{-1})	Organic carbon (%)	N	P	K	Bulk density (Mg m^{-3})
Stale seedbed + Hand weeding (20 & 40 DAS)	7.80	0.28	0.50	196	20.5	362	1.31
Intercrop Greengram	7.84	0.32	0.54	189	18.8	352	1.28
Sunhemp mulch	7.83	0.29	0.56	192	19.5	357	1.29
Weed mulch	7.87	0.27	0.50	188	18.7	348	1.30
Straw mulch	7.80	0.31	0.55	187	18.5	346	1.29
Farmer practices	7.80	0.32	0.49	183	18.1	343	1.31
Weedy check	7.83	0.29	0.47	181	18.0	340	1.33
SEm ($\pm$)	0.23	0.02	0.03	1.73	0.42	3.89	0.07
CD at 5 %	NS	NS	NS	5.33	1.31	11.99	NS
Initial	7.78	0.27	0.45	179	17.4	333	1.35

Table 6. Soil biological indicators as influenced by weed management practices

Treatment	SMBC ($\mu\text{g g}^{-1}$)	SMBN ($\mu\text{g g}^{-1}$)	DHA ($\mu\text{g TPF g}^{-1} 24 \text{ hr}^{-1}$)	No. of earthworms (m^{-2})
Stale seedbed + Hand weeding (20 & 40 DAS)	210	40	49	1.6
Intercrop Greengram	206	37	50	1.7
Sunhemp mulch	207	40	52	1.8
Weed mulch	203	37	48	1.6
Straw mulch	210	41	51	1.7
Farmer practices	191	36	47	1.6
Weedy check	177	25	41	1.5
SEm ($\pm$)	5.89	1.52	1.70	0.18
CD at 5 %	18.15	4.68	5.24	NS

height, number of sympodial branches, leaf area and dry matter accumulation per plant, along with their subsequent translocation to sinks. However, the greater number of bolls per plant under farmer practices, stale seedbed and straw mulch treatments might be due to enhanced moisture availability and nutrient uptake, which improved photosynthesis, leaf expansion and translocation of assimilates to reproductive parts. These findings are consistent with earlier reports (9, 10, 15).

The higher seed cotton yield observed in the stale seedbed with 2 hand weedings can be attributed to the elimination of initial weed flushes through shallow tillage, which created a competition-free environment favourable for seed germination, seedling emergence and crop establishment (16). Additionally, the use of mulch helps retain soil moisture and suppress weed growth, thereby contributing to increased crop productivity. Similar findings have been reported in earlier studies (9, 10, 17, 18). Fibre quality is a key determinant of cotton price and, although largely genetically controlled, it is influenced by environmental and management factors. Straw mulch improved fibre quality, possibly by enhancing moisture availability and reducing stress, thereby supporting boll retention and fibre elongation. Similar results have been reported previously (19).

The lowest EC was found under application of weed mulch (0.27) and the highest was recorded with farmer practices (0.32) and intercrop mulch (0.32). This might be due to the inclusion of legumes as an intercrop or sequence crop, along with *in-situ* moisture conservation measures, which significantly improved soil health and related properties. These findings are consistent with previous reports (20). The highest content was recorded with the application of sunhemp mulch (0.56), followed by straw mulch (0.55). This might be due to the addition of organic matter through intercrop biomass, leaf litter decomposition and other applied organic sources, which enhanced soil microbial activity, resulting in increased soil organic carbon content. Similar findings have been reported in previous studies (21–24). Higher bulk density was found under farmer practices, whereas lower values were observed under different mulch treatments. The decrease in bulk density was associated with an improvement in per cent water-stable aggregates, attributed to increased moisture availability and improved soil structure. The reduction in soil bulk density was mainly due to higher organic carbon content and enhanced microbial activity under mulch practices. These results are in agreement with previous studies (25, 26).

SSB with twice hand weeding enhanced the total N, P and K uptake, followed by sunhemp mulch. Higher uptake of nutrients recorded under SSB may be attributed to increased dry matter production. The lower weed density under this effective pre-sowing weed management practice may have reduced weed competition throughout the crop period, thereby facilitating greater nutrient uptake by cotton (8, 27, 28). The uptake of major nutrients was influenced by dry matter production, nutrient availability and nutrient concentration in plant tissues (17, 18, 24). Improvement in the dehydrogenase activity under sunhemp mulch, followed by straw mulch in the rhizosphere of crops at the grand growth stage, might be because of *in situ* green manuring of sunhemp and the addition of biomass through straw mulch. These findings are consistent with earlier reports (21). The increase in SMBC and SMBN during the grand growth stage is likely due to *in-situ* green manuring with sunhemp and the addition of

crop residues, which supply nutrients and energy for microbial growth. Improved organic matter and moisture levels further support microbial growth and mineralization, leading to increased microbial biomass and water-soluble carbon in the soil. These findings are consistent with earlier reports (26, 29, 30). The highest earthworm population was observed under sunhemp mulch, due to the availability of residual biomass serving as feed for earthworms along with improved soil moisture conditions supporting their activity. Similar findings have been reported earlier (31).

Conclusion

The stale seedbed treatment was most effective in controlling weeds, as evidenced by the lowest weed density and the highest weed control efficiency. Among the mulching options, straw mulch resulted in the highest net returns and the most favourable benefit-cost ratio. At the same time, farmer practices yielded the highest gross monetary returns, closely followed by stale seedbed with twice hand weeding. Integrating practices such as stale seedbed, straw mulch and green manuring significantly improved cotton growth, yield, fibre quality and soil health. These treatments enhanced moisture retention, nutrient uptake and microbial activity, reducing weed pressure and improving soil properties such as organic carbon content, bulk density and biological activity. Together, these benefits contributed to improved productivity and profitability, thereby supporting sustainable cotton cultivation.

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Authors' contributions

WVG, PVS and JSM designed the study, developed the technique, conducted the investigation and prepared the original draft. VC participated in study design, manuscript preparation, review and editing. VKC and NC were involved in methodology development, data analysis and supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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