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RESEARCH ARTICLE

Comparative evaluation of mechanized cultivation with conventional method on soil and plant nutrients and yield of sesame

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Abstract

A field experiment was conducted at the Regional Research Station, Vriddhachalam, India, during the summer of 2023, kharif 2023 and summer season of 2024 to evaluate the yield and nutrient dynamics of mechanized sesame (*Sesamum indicum* L.) cultivation. The experiment consisted of four crop establishment methods in the main plot: Inclined plate planter with pelletized seeds (M_1), Pneumatic precision planter with pelletized seeds (M_2), Pneumatic precision planter without pelletized seeds (M_3) and Manual line sowing (M_4) and four weed management and harvesting methods were assigned to the subplot: Quizalofop ethyl + reaper binder (S_1), Quizalofop ethyl + manual harvest (S_2), Hand weeding + reaper binder (S_3) and Hand weeding + manual harvest (S_4) in a split-plot design with three replications. Three seasonal results revealed that line sowing (M_4) consistently outperformed other crop establishment techniques regarding seed and stalk yields and nutrient uptake of sesame at 30 days after sowing (DAS), 60 DAS and maturity stages. Hand weeding with either reaper binder (S_3) or manual harvesting (S_4) recorded the best results in sesame yield and nutrient uptake. Concerning post-harvest soil nutrient status, the crop establishment method by Pneumatic precision planter without pelletized seeds (M_3) and in terms of weed management and harvesting method, Quizalofop ethyl + manual harvest (S_2) recorded higher post-harvest soil available nutrient status. Hence, it is inferred that sowing sesame in lines and performing manual weeding and harvesting it either manually or using a reaper binder is the best combination that foraged the maximum nutrients and increased yields.

Keywords

line sowing; nutrient uptake; post-harvest soil analysis; quizalofop ethyl; reaper binder; sesame

Introduction

Sesame (*Sesamum indicum* L.) is an important oilseed crop in India. It is widely grown in different regions due to its adaptability to a wide range of environmental conditions and the premium quality of its edible oil. This oil contains vitamins, essential amino acids and polyunsaturated fats. Specifically, linoleic and oleic acids are the main elements in sesamum seeds, playing a vital role in determining the consistency and quality of the oil. Sesame is aptly titled as 'Queen of Oilseeds' due to its high levels of polyunsaturated fatty acids, which give it a natural resistance to rancidity (1). Sesame oil contains key nutrients, including methionine, tryptophan, niacin and minerals like calcium and phosphorus (P). The strong antioxidant properties in seeds enhance the oil's shelf life, leading to its reputation as the 'seeds of immortality' (2). Despite its significance, global sesame productivity remains suboptimal, particularly in developing countries like India. India, the world's fifth-largest oilseed producer, contributes only 6-7 % to global oilseed production, with sesame productivity averaging 405 kg/ha (3). The lower productivity is mainly because sesame is grown as a rainfed crop with poor usage of agronomic practices. In many areas, it is sown broadcasting with minimal or no application of herbicides and improper weed management. Furthermore, mechanized harvesting prevents yield loss caused by seed shattering due to over-ripening capsules in the field, a common issue when manual labour is scarce at harvest (4).

Mechanized farming offers numerous benefits over traditional methods, including increased efficiency, reduced labor costs and improved safety. Mechanization facilitates more accurate sowing, effective weed control and timely harvesting, all of which enhance yields and improve economic returns. It alleviates the physical burden on farmers and guarantees the efficient execution of essential agricultural tasks such as sowing and harvesting, hence averting production losses (5). Manual sowing often delays the process, leading to dry soil conditions, poor plant populations and low yields. Through precision seed drills or seeders, mechanized sowing ensures timely planting, optimal seed placement and better spacing, promoting healthier plant growth and higher yields (6). Weed management also gets benefits from herbicide application. Applying pre-emergence herbicides controls early weed growth, while post-emergence herbicides tackle late-emerged weeds (7,8). This reduces manual labor and ensures uniform crop growth, enhancing yield potential.

Nutrient availability and crop uptake are crucial indicators in any research work. Higher nutrient availability supports the increased nutrient concentration in the plants, which ultimately enhances the dry matter production of plants. Nutrient concentration and dry matter production ultimately influence the uptake of the sesame and the increase or decrease of these directly influences the uptake (9). Given this context, there is a critical need to investigate the impact of agricultural mechanization on nutrient uptake, post-harvest soil available nutrient status and yield of sesame.

Materials and Methods

Experimental site

The field study was carried out at the Regional Research Station in Vriddhachalam, Tamil Nadu, India, during the summer 2023 (March to May), kharif 2023 (June to September) and summer 2024 (February to May) growing seasons. The research site is geographically positioned at 11°30'N latitude and 79°26'E longitude, with an elevation of 46.7 meters above mean sea level. The weather data, summarized in Table 1, revealed that rainfall was considerably higher during Kharif 2023 compared to the summer seasons. All other weather factors were favorable for sesame cultivation and there was little variation between seasons.

Initial soil samples collected before the experiment across the three seasons showed a neutral pH (7.5-7.6) and non -saline conditions, with electrical conductivity ranging between 0.96 and 1.18 dS m^{-1}. The soil had low levels of available nitrogen (N) (157.2-179.5 kg/ha), moderate levels of available P (14.3-17.3 kg/ha) and high levels of available potassium (K) (185.3-201.3 kg/ha).

Treatment details and experimental setup

The field experiment employed a split-plot design featuring four main plot (M) treatments and four subplot (S) treatments, each replicated three times. The main plot treatments involved various crop establishment methods, namely, Inclined plate planter using pelletized seeds (M_1), Pneumatic precision planter using pelletized seeds (M_2), Pneumatic precision planter using non-pelletized seeds (M_3) and Manual line sowing using non-pelletized seeds (M_4). The subplot treatments comprised different weed management and harvesting methods, such as applying Quizalofop ethyl 5 % EC at 50 g a.i. ha^{-1} at 20 DAS followed by harvesting with a reaper binder (S_1), application of Quizalofop ethyl 5 % EC at 50 g a.i. ha^{-1} at 20 DAS with manual harvesting (S_2), hand weeding at 30 DAS combined with reaper binder for harvest (S_3) and hand weeding at 30 DAS followed by manual harvest (S_4). Additionally, all plots received a pre-emergence herbicide, pendimethalin 30 % EC at 0.75 kg a.i. ha^{-1}, applied at 3 DAS.

Table 1. Weather prevailed during the cropping seasons

S. No.	Weather parameters	Summer 2023	Kharif 2023	Summer 2024
1.	Maximum temperature	35.9 °C	36.1 °C	36.2 °C
2.	Minimum temperature	24.5 °C	25.5 °C	26.2 °C
3.	Total rainfall	202.2 mm received in seven rainy days	296.7 mm received in 18 rainy days	65.8 mm received in three rainy days
4.	Relative humidity	92.4 % at 07:12 hrs 67.6 % at 14:12 hrs	90.3 % at 07:12 hrs 65.0 % at 14:12 hrs	92.0 % at 07:12 hrs 64.3 % at 14:12 hrs
5.	Average sunshine hours	7.4 day^{-1}	6.1 day^{-1}	7.6 day^{-1}
6.	Evaporation	5.1 mm day^{-1}	4.1 mm day^{-1}	5.1 mm day^{-1}
7.	Wind speed	3.1 km h^{-1}	2.7 km h^{-1}	3.8 km h^{-1}

Agronomic practices

The sesame variety chosen for the field experiment was VRI 4, which has a growth period of 85-90 days. To protect against seed-borne diseases, high-quality sesame seeds were treated with *Trichoderma viride* at 4 g kg^{-1} of seed. Seed pelleting was performed using the TNAU seed pelleting mixture according to the specified treatments (M_1 and M_2) to ensure uniform seed size for precision planting with seed drills. Farmyard manure (FYM) was applied at 12.5 tons ha^{-1} across all treatments. Additionally, a fertilizer dosage of 35:23:23 kg/ha of N, P and potassium (K) was used uniformly in all treatments. The fertilizers used included urea (46 % N), single super phosphate (16 % P_2O_5) and muriate of potash (60% K_2O).

Nitrogen was applied in two stages. Half of the N and total doses of P and K were mixed into the soil at sowing as basal application. The remaining N was applied as a top dressing 30 DAS. Irrigation was provided as necessary throughout the growing season.

Weed control strategies, including manual weeding and herbicide application, were carried out according to the specific treatment protocols. To address pest issues, especially the vectors causing sesame phyllody, foliar sprays of Imidacloprid 17.8 % SL (0.2 ml litre^{-1} of water) were applied at 45 DAS, followed by Thiamethoxam 25 WG (0.2 g litre^{-1} of water) at 60 DAS. Harvesting was performed using various methods based on the treatment, such as manual harvesting (traditional) and mechanical harvesting with a reaper binder.

Yield analysis

All the plants from the designated net plot area for each treatment were harvested, sun-dried, threshed, cleaned and weighed to determine seed yield (kg/ha). The above-ground biomass (excluding capsules) from the same plot area was also collected, sun-dried and weighed to determine stalk yield (kg/ha).

Nitrogen uptake

The N content of plant samples was estimated using the micro Kjeldhal method (10) and recorded in percentages. The total N uptake was computed by multiplying N content (%) with dry-matter production of the respective treatment and recorded in kg/ha at 30 and 60 DAS and maturity stages.

Phosphorus uptake

The P content in the plant sample was determined by the triple acid digestion method (11) with a spectrophotometer. From the standard curve drawn, the P content (%) was calculated and the uptake was computed by multiplying with respective dry matter production and expressed in kg/ha at 30 and 60 DAS and maturity stages.

Potassium uptake

The flame photometer estimated the plant sample's K content (%) using the triacid mixture (11). The sample's K content (%) was calculated from the standard curve drawn. The uptake was computed by multiplying with respective dry matter production and expressed in kg/ha at 30 and 60 DAS and the maturity stage.

Post-harvest soil nutrient analysis

Immediately after harvesting the sesame crop, soil samples were drawn randomly from each treatment plot, dried under shade and analysed for available N (12), available P (13) and available K (11).

Statistical Analysis

The data obtained were subjected to statistical analysis (14) using AGRES software version 7.0. If the treatment differences were found significant (S), critical differences (CD) were worked out at a five percent probability level. Treatment differences that were not significant are denoted as NS.

Results

Yield

The different planting methods made significant variations in sesame seed yield (Fig.1). The traditional line sowing (M_4) technique demonstrated superior performance (811 kg/ha), surpassing other mechanized approaches during the summer 2023 season. Specifically, line sowing outperformed the inclined plate planter with pelleted seeds (M_1), pneumatic precision planter with pelleted seeds (M_2) and pneumatic precision planter with non-pelleted seeds (M_3) by 6.90 %, 12.94 % and 18.86 % respectively in seed yield. Similar trends were observed in Kharif 2023, with yield improvements of 6.90 %, 13.28 % and 19.40 % for line sowing over M_1, M_2 and M_3, respectively and the summer 2024 season exhibited comparable patterns. The enhanced productivity in line-sown sesame can be attributed to improved germination rates, consistent plant establishment, robust growth and favorable yield. These factors collectively contributed to increased seed and biomass production compared to machine-sown methods. Manual line sowing enhanced uniform seed germination and promoted early seedling establishment in sesame. This method supported more significant dry-matter accumulation and the formation of thicker basal nodes.

Furthermore, it encouraged the growth of more primary and secondary branches, leading to an expanded leaf area and improved photosynthetic efficiency. Finally, these factors collectively contribute to better yield attributes and higher yields. In contrast, another study reported that mechanical planting of pelletized sesame seeds using a pneumatic precision planter achieved a higher yield than the line sowing method (15).

A significant difference was noted in stalk yield under various crop establishment techniques (Fig. 2). It was observed that line-sown sesame (M_4) significantly enhanced the stalk yield (2625 kg/ha) over other methods *viz.,* the inclined plate planter with pelleted seeds, pneumatic precision planter with pelleted seeds and pneumatic precision planter with un pelleted seeds by 6.93 %, 13.25 % and 19.96 % respectively during summer 2023. Similar trends were observed during the Kharif 2023 and summer 2024 seasons. Seed yield and stalk yield exhibited strong positive correlations suggesting that an increase in one of these variables is likely accompanied by an increase in the other (Fig. 3).

The reduced seed and stalk yields observed in machine-sown sesame, particularly with the pneumatic precision planter using non-pelleted seeds (M_3), were primarily due to suboptimal growth and yield attributes. However, contrasting

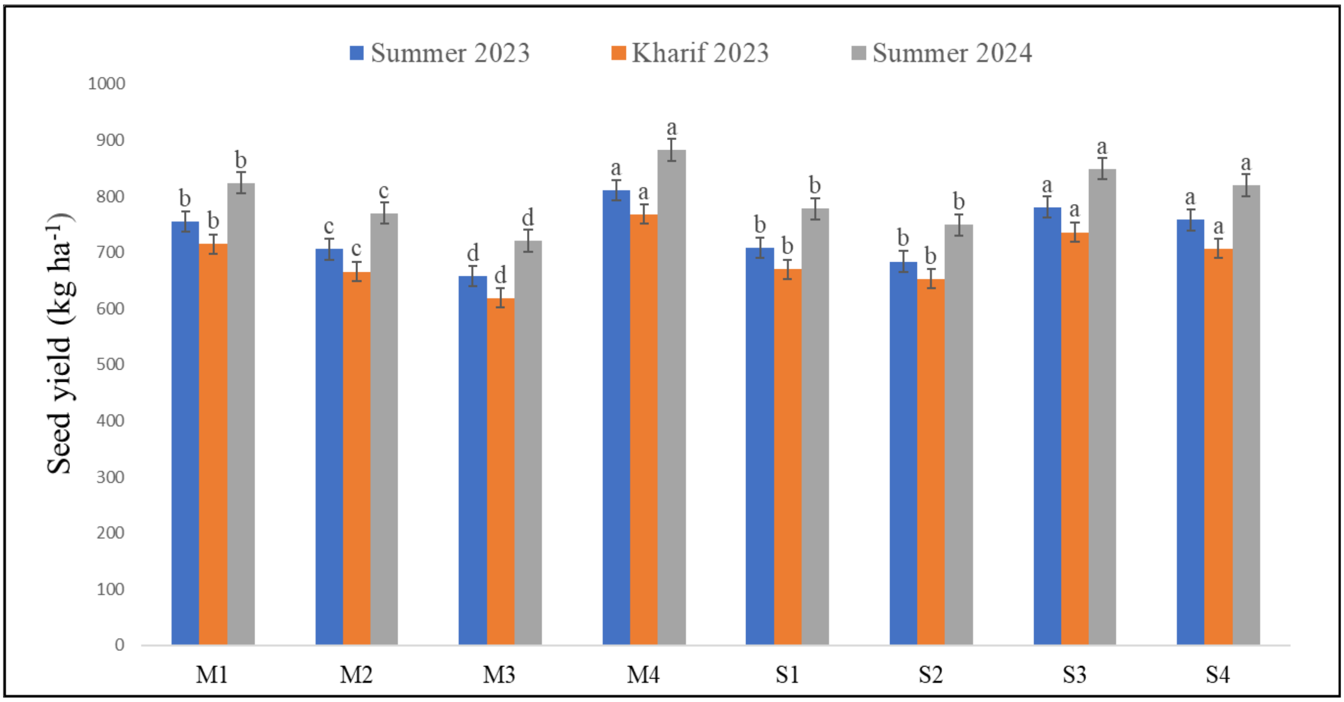

Fig. 1. Effect of different crop establishment techniques, weed management and harvesting methods on seed yield of sesame.

Main plot: M_1- Inclined plate planter using pelletized seeds, M_2- Pneumatic precision planter using pelletized seeds, M_3- Pneumatic precision planter using non-pelletized seeds (M_3) and M_4- Manual line sowing; Subplot: S_1- Quizalofop ethyl 5% EC at 50 g a.i. ha^{-1} at 20 DAS + harvesting with a reaper binder, S_2- Quizalofop ethyl 5% EC at 50 g a.i. ha^{-1} at 20 DAS + manual harvesting, S_3- hand weeding at 30 DAS + reaper binder for harvest and S_4- hand weeding at 30 DAS + manual harvest.

Error bars indicate the standard errors (SE) of the means. Treatments sharing the same letter are not significantly different ($p < 0.05$), using DMRT.

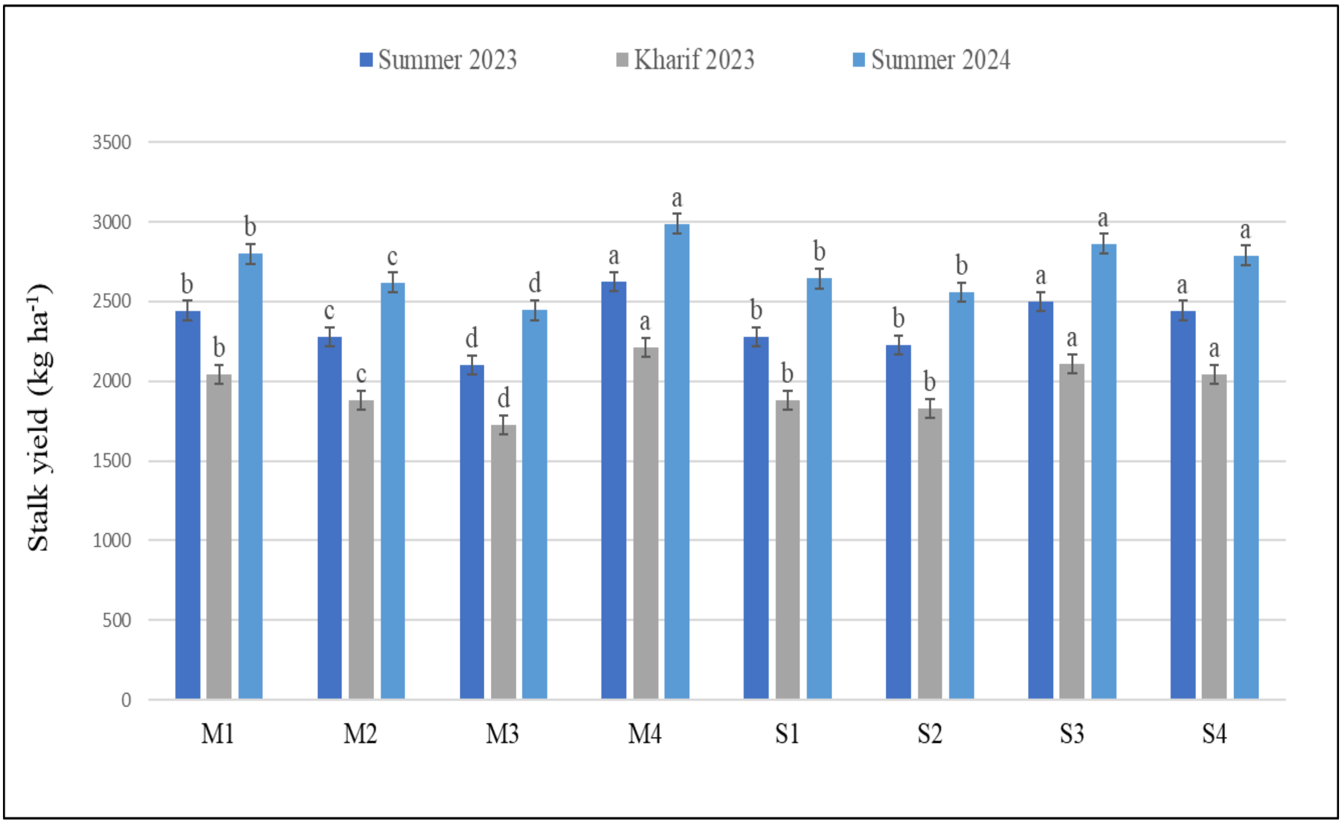

Fig. 2. Effect of different crop establishment techniques, weed management and harvesting methods on stalk yield of sesame.

Main plot: M1 - Inclined plate planter using pelletized seeds, M2 - Pneumatic precision planter using pelletized seeds, M3 - Pneumatic precision planter using non-pelletized seeds (M3) and M4 - Manual line sowing; Subplot: S1 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + harvesting with a reaper binder, S2 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + manual harvesting, S3 - hand weeding at 30 DAS + reaper binder for harvest and S4 - hand weeding at 30 DAS + manual harvest.

Error bars indicate the standard errors (SE) of the means. Treatments sharing the same letter are not significantly different ($p < 0.05$), using DMRT

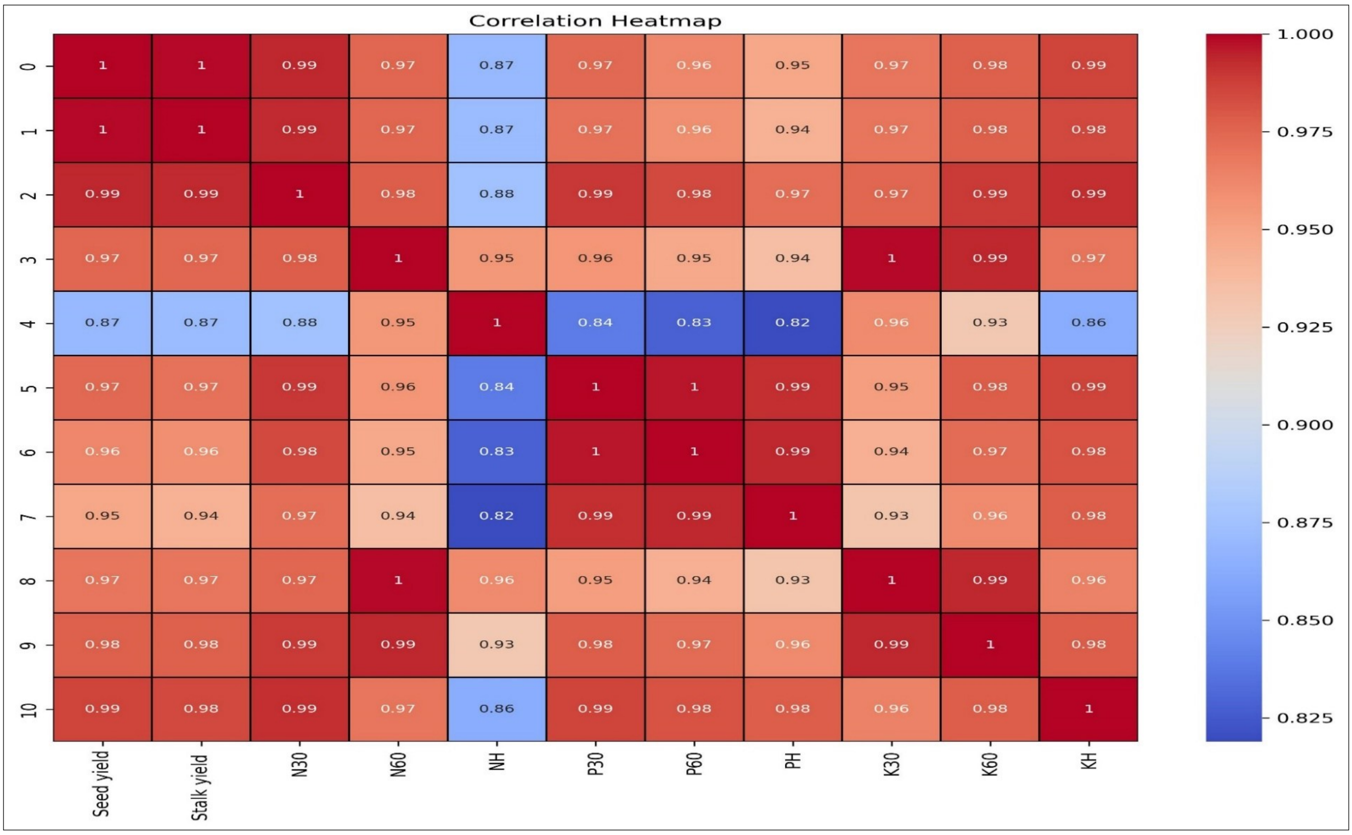

Fig. 3. Correlation matrix depicting the relationship among yield and nutrient uptake of mechanized sesame cultivation.

N30-N uptake at30DAS, N60-N uptake at60DAS, NH-N uptake at maturity stage, P30-P uptake at30DAS, P60-P uptake at60DAS, PH-P uptake @maturity stage, K30-K uptake at30DAS, K60- K uptake at60DAS, KH- K uptake at maturity stage.

results, where mechanized planting of pelleted sesame seeds using a pneumatic precision planter yielded better outcomes than line sowing (16).

Significant variations in sesame seed yield were also observed across different combinations of weed control and harvesting techniques over three growing seasons (Fig.1). Treatments involving manual weeding at 30 DAS, combined with either mechanical harvesting using a reaper binder (S_3) or traditional manual harvesting (S_4), consistently produced higher seed and stalk yields across all three seasons compared to other treatments. In the summer 2023, S_3 (781 kg/ha) increased seed yield by 9.34 % and 12.41% compared to S_1 (708 kg/ha) and S_2 (684 kg/ha), respectively, while S_4 (758 kg/ha) showed improvements of 6.59 % and 9.76 %. Similar patterns were observed in the kharif 2023 and summer 2024 seasons. Stalk yield was also identical to the seed yield across seasons. These yield improvements could be attributed to reduced weed presence and competition throughout the crop's growth and reproductive phases, positively impacting photosynthate accumulation and enhancing yield components and overall seed production. It was also noted that better uptake of nutrients (N, P and K) due to efficient weed management, as evidenced in the present study, supports the investigation results (Fig. 3). A significant and positive correlation between nutrient uptake such as N, P and K and seed yield confirms the relationship. The findings of a previous study reported similar results in winter-sown sesame (17).

The lowest seed and stalk yields were recorded in treatments using quizalofop ethyl 5% EC at 50 g a.i. ha^{-1} applied 20 DAS, combined with manual harvesting (S_2). In comparison to manual weeding, this subpar performance was chiefly attributed to insufficient weed management, especially for broad-leaved weeds and sedges, which corroborated previous reports (18).

No interaction effect was found in sesame yields among M × S (establishment methods × weed management and harvesting methods) across seasons.

Nitrogen uptake

A significant difference in N uptake by sesame at 30 and 60 DAS and maturity stages was observed across the various crop establishment techniques tested (Table 2). Line-sown sesame (M_4) significantly increased N uptake (7.37 kg/ha, 18.67 kg/ha, and 23.62 kg/ha) at 30, 60 DAS and harvest, respectively, during the initial season (summer 2023) over other methods. Similar results were recorded in the subsequent kharif 2023 and summer 2024 seasons. The increased N uptake in manually sown sesame could be attributed to improved root development due to optimal spacing, which enhanced soil-plant interactions and overall plant vigor. This likely led to more efficient nutrient absorption, enabling the plants to extract and utilize N more effectively from the soil throughout their growth cycle (19).

The treatment that involved hand weeding at 30 DAS of sesame along with the harvesting by reaper binder (S_3) recorded a significantly higher N uptake (7.11 kg/ha, 18.13 kg/ha and 23.37 kg/ha) at 30, 60 DAS and harvest respectively over other treatments during summer 2023 season. However, it was statistically at par with hand weeding at 30 DAS followed by manual harvesting (S_4). A similar trend was observed during the following seasons (kharif 2023 and summer 2024). The advantage of hand weeding offers precision control, which allows for the complete removal of both broad-leaved weeds and grasses that herbicides like quizalofop ethyl might not fully

Table 2. Effect of different crop establishment techniques, weed management and harvesting methods on N uptake of sesame

Treatments	N uptake at 30 DAS (kg/ha)			N uptake at 60 DAS (kg/ha)			N uptake at harvest (kg/ha)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	6.41	6.19	6.83	17.21	16.63	18.05	21.88	19.32	23.22
M_2	5.58	5.41	5.94	16.03	15.51	16.73	20.11	17.47	21.63
M_3	4.63	4.46	5.11	14.88	14.32	15.56	18.69	16.02	20.07
M_4	7.37	7.04	7.95	18.67	17.94	19.58	23.62	21.55	25.13
S.Em. ±	0.21	0.20	0.22	0.29	0.28	0.31	0.37	0.39	0.4
C.D. (P=0.05)	0.74	0.69	0.76	1.01	0.97	1.06	1.28	1.34	1.37
Sub plots (S)									
S_1	5.67	5.35	5.81	16.45	16.23	17.23	21.23	20.43	23.11
S_2	5.23	4.88	5.27	16.07	15.86	16.78	20.75	19.97	22.75
S_3	7.11	6.93	7.22	18.13	17.95	19.07	23.37	22.28	25.11
S_4	6.75	6.49	6.76	17.66	17.48	18.55	22.86	21.83	24.72
S.Em. ±	0.23	0.22	0.24	0.35	0.35	0.37	0.45	0.43	0.49
C.D. (P=0.05)	0.67	0.64	0.7	1.02	1.01	1.08	1.32	1.26	1.44

Interaction absent

Main plot: M1 - Inclined plate planter using pelletized seeds, M2 - Pneumatic precision planter using pelletized seeds, M3 - Pneumatic precision planter using non-pelletized seeds (M3) and M4 - Manual line sowing; Subplot: S1 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + harvesting with a reaper binder, S2 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + manual harvesting, S3 - hand weeding at 30 DAS + reaper binder for harvest and S4 - hand weeding at 30 DAS + manual harvest.

control. Manual weeding also minimizes the risk of herbicide resistance development and offers better soil aeration, promoting root health and nutrient absorption, particularly for N. As N plays a crucial role in photosynthesis and growth, better weed control offers improved N uptake. The earlier findings also concluded that the pre-emergence application of pendimethalin at 0.75 kg/ha supplemented with hand weeding at 30 DAS recorded significantly higher nutrient uptake by sesame in sandy loam soils (20).

In contrast, the treatments involving quizalofop ethyl resulted in lower N uptake, likely due to inadequate weed control leading to higher competition for nutrients. This aligns with previous studies that highlight the negative impact of poor weed management on nutrient absorption in sesame crops (21).

Irrespective of the crop growth stages, no interaction effect was found in the N uptake of sesame among M × S (establishment methods × weed management methods and harvesting methods) across any seasons.

Phosphorus uptake

The data presented in Table 3 revealed a significant variation in P uptake by sesame at 30, 60 DAS and harvest across the different crop establishment techniques evaluated. During the summer 2023 season, sesame sown in rows (M_4) exhibited significantly enhanced P uptake at 30 DAS (2.78 kg/ha), 60 DAS (5.83 kg/ha) and harvest (7.63 kg/ha) compared to other methods. The subsequent kharif 2023 and summer 2024 seasons also exhibited similar trends, with row sowing consistently demonstrating higher P uptake than the different planting techniques. The increased P uptake in line-sown

Table 3. Effect of different crop establishment techniques, weed management and harvesting methods on P uptake of sesame

Treatments	P uptake at 30 DAS (kg/ha)			P uptake at 60 DAS (kg/ha)			P uptake at harvest (kg/ha)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	2.27	2.04	2.36	5.23	5.11	5.37	6.88	6.35	7.21
M_2	1.83	1.62	1.95	4.68	4.69	4.83	6.21	5.71	6.56
M_3	1.24	1.17	1.41	4.21	4.25	4.38	5.60	5.05	5.93
M_4	2.78	2.63	2.91	5.83	5.62	5.93	7.63	7.11	7.98
S.Em. ±	0.07	0.06	0.07	0.12	0.11	0.12	0.16	0.15	0.17
C.D. (P=0.05)	0.24	0.21	0.24	0.41	0.39	0.41	0.55	0.52	0.58
Sub plots (S)									
S_1	1.65	1.52	1.74	4.63	4.41	4.71	6.33	6.01	6.42
S_2	1.47	1.35	1.57	4.38	4.16	4.48	6.04	5.79	6.19
S_3	2.65	2.51	2.83	5.66	5.57	5.85	7.48	7.07	7.86
S_4	2.51	2..33	2.66	5.42	5.32	5.63	7.13	6.83	7.53
S.Em. ±	0.08	0.07	0.08	0.14	0.13	0.14	0.19	0.18	0.19
C.D. (P=0.05)	0.23	0.21	0.23	0.41	0.38	0.41	0.55	0.52	0.55

Interaction absent

Main plot: M1 - Inclined plate planter using pelletized seeds, M2 - Pneumatic precision planter using pelletized seeds, M3 - Pneumatic precision planter using non-pelletized seeds (M3), and M4 - Manual line sowing; Sub plot: S1 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + harvesting with a reaper binder, S2 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + manual harvesting, S3 - hand weeding at 30 DAS + reaper binder for harvest and S4 - hand weeding at 30 DAS + manual harvest.

sesame might be attributed to the improved seedling establishment and root development, which enhances nutrient absorption from the soil. The uniform distribution of plants in line sowing could also contribute to efficient nutrient utilization, thereby boosting P uptake (22).

The treatment involving hand weeding at 30 DAS of sesame, combined with harvesting using a reaper binder (S_3), demonstrated significantly higher P uptake (2.65 kg/ha at 30 DAS, 5.66 kg/ha at 60 DAS and 7.48 kg/ha at harvest) compared to other treatments. This treatment was comparable to hand weeding at 30 DAS, followed by manual harvesting (S_4). Similar results were observed in the subsequent kharif 2023 and summer 2024 seasons. This could be attributed to better weed control during the critical growth stages of sesame. Effective weed management reduces competition for nutrients, especially P, allowing sesame plants to absorb higher quantities. The superior performance of S_3 and S_4 treatments compared to chemical weed control methods (S_1 and S_2) underscores the importance of manual weeding in enhancing nutrient uptake, likely due to its ability to manage both broadleaf and grassy weeds more efficiently (23). These results align with previous results (24), which reported that the nutrient uptake by the sesame crop under hand weeding was the highest P uptake of 20.4 kg/ha by the sesame crop.

No interaction effect was observed on P uptake by sesame in crop growth stages between the combinations of establishment methods, weed management strategies and harvesting techniques across all seasons.

Potassium uptake

A significant difference in K uptake by sesame was noted at 30 DAS, 60 DAS and harvest across the various crop establishment techniques evaluated (Table 4). Line-sown sesame (M_4) exhibited K uptakes of 6.85 kg/ha at 30 DAS, 12.83 kg/ha at 60 DAS and 15.61 kg/ha at harvest, significantly higher than those recorded for other methods. Line sowing could have promoted better root development and nutrient accessibility by ensuring optimal seed placement and spacing which allows sesame plants to establish a more efficient root system. This method minimized competition between plants for nutrients, enabling them to more effectively absorb essential elements like N, P and K. Potassium plays a key role in enzyme activation, photosynthesis and overall plant health (25). Higher K availability could have improved plant resilience and productivity, leading to healthier growth. These benefits were consistently observed in both the Kharif 2023 and summer 2024 seasons.

Among weed control and harvesting methods, hand weeding at 30 DAS followed by either reaper binder harvesting (S_3) or manual harvesting (S_4), registered significantly higher K uptake of 6.63 kg/ha at 30 DAS, 12.48 kg/ha at 60 DAS and 14.81 kg/ha at harvest. The higher K uptake observed in these treatments could be attributed to several factors. Hand weeding at 30 DAS reduced early weed competition for nutrients, light and space, allowing sesame plants to grow more vigorously and access soil K more effectively. This improved root health and soil aeration and enabled better nutrient absorption. Additionally, using a reaper binder (S_3) for harvesting likely improved post-harvest residue management, reducing soil compaction, retaining organic matter and promoting nutrient cycling, which could have supported K availability. Decreasing chemical herbicide application and limiting early weed competition may have created conditions favorable for enhanced nutrient absorption and plant productivity. Comparable outcomes were noted in the identical treatment during Kharif 2023 and summer 2024. The increased K uptake associated with hand weeding in sesame corresponds with findings from an additional study (26).

Regardless of the crop's growth stages, no interaction effect on K uptake in sesame was observed between the combinations of establishment methods, weed control methods and harvesting techniques across seasons.

Post-harvest soil available nutrient status

The data in Table 5 revealed a significant variation in post-harvest soil available nutrient status across the different crop establishment techniques, weed management and harvest methods.

Table 4. Effect of different crop establishment techniques, weed management and harvesting methods on K uptake of sesame

Treatments	K uptake at 30 DAS (kg/ha)			K uptake at 60 DAS (kg/ha)			K uptake at harvest (kg/ha)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	5.73	5.58	5.86	11.66	11.31	11.81	13.88	13.61	14.82
M_2	4.66	4.49	4.79	10.65	10.28	10.76	12.62	12.33	13.51
M_3	3.71	3.53	3.83	9.56	9.23	9.75	11.47	11.08	12.15
M_4	6.85	6.72	6.98	12.83	12.35	12.98	15.61	14.97	16.28
S.Em. ±	0.24	0.22	0.25	0.26	0.25	0.26	0.32	0.30	0.33
C.D. (P=0.05)	0.83	0.76	0.87	0.91	0.87	0.92	1.09	1.04	1.16
Sub plots (S)									
S_1	5.11	5.07	5.37	10.75	10.63	11.23	12.71	12.11	13.56
S_2	4.76	4.62	4.82	10.37	10.22	10.76	12.19	11.78	12.90
S_3	6.63	6.51	6.87	12.48	12.28	12.85	14.81	13.63	15.74
S_4	6.25	6.18	6.52	11.93	11.87	12.41	14.57	13.27	15.29
S.Em. ±	0.22	0.21	0.22	0.31	0.27	0.32	0.37	0.35	0.39
C.D. (P=0.05)	0.64	0.61	0.64	0.91	0.79	0.94	1.08	1.02	1.14

Interaction absent

Main plot: M1 - Inclined plate planter using pelletized seeds, M2 - Pneumatic precision planter using pelletized seeds, M3 - Pneumatic precision planter using non-pelletized seeds (M3) and M4 - Manual line sowing; Sub plot: S1 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + harvesting with a reaper binder, S2 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + manual harvesting, S3 - hand weeding at 30 DAS + reaper binder for harvest and S4 - hand weeding at 30 DAS + manual harvest.

Table 5. Effect of different crop establishment techniques, weed management and harvesting methods on post-harvest soil available nutrients

Treatments	Soil available N (kg/ha)			Soil available P (kg/ha)			Soil available K (kg/ha)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	162.7	161.2	170.8	23.05	22.08	23.78	190.7	187.5	179.6
M_2	165.6	164.3	176.5	24.12	23.17	25.08	194.8	192.6	184.2
M_3	170.2	168.5	183.6	25.78	24.46	26.53	201.5	198.2	190.3
M_4	160.1	158.4	165.3	21.87	20.95	22.56	186.3	182.8	174.1
S.Em. ±	0.6	0.5	0.7	0.24	0.22	0.26	1.0	0.9	1.1
C.D. (P=0.05)	2.1	1.7	2.4	0.83	0.76	0.90	3.5	3.1	3.8
Sub plots (S)									
S_1	166.3	163.7	175.5	22.45	21.32	23.11	196.4	195.6	183.7
S_2	170.2	168.5	182.6	23.67	22.58	24.22	202.5	200.8	189.3
S_3	158.7	155.3	167.2	20.42	19.33	21.27	187.8	186.7	173.2
S_4	163.2	160.2	171.8	21.53	20.46	22.33	192.1	191.2	177.5
S.Em. ±	0.9	0.8	1.0	0.19	0.18	0.19	1.2	1.1	1.3
C.D. (P=0.05)	2.6	2.3	2.9	0.55	0.52	0.55	3.5	3.2	3.8

Interaction absent

Main plot: M1 - Inclined plate planter using pelletized seeds, M2 - Pneumatic precision planter using pelletized seeds, M3 - Pneumatic precision planter using non-pelletized seeds (M3) and M4 - Manual line sowing; Subplot: S1 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + harvesting with a reaper binder, S2 - Quizalofop ethyl 5% EC at 50 g a.i. ha-1 at 20 DAS + manual harvesting, S3 - hand weeding at 30 DAS + reaper binder for harvest and S4 - hand weeding at 30 DAS + manual harvest.

During the summer 2023 season, sesame sown by a pneumatic precision planter with non-pelleted seeds (M_3) exhibited significantly high available N (170.2 kg/ha), P (25.78 kg/ha) and K (201.5 kg/ha) in the soil after sesame harvest, compared to other methods. The subsequent Kharif 2023 and summer 2024 seasons also exhibited similar trends. The higher residual N, P and K in the soil could be attributed to poor crop establishment. This low plant stand might be due to uneven germination and weak seedling growth resulting in fewer plants to absorb the available nutrients. As a result, higher nutrients remained in the soil after harvest. Similar results were observed in earlier studies (27).

Among weed management and harvest methods, quizalofop ethyl 5 % EC was applied at 50 g a.i. ha^{-1} applied 20 DAS, combined with manual harvesting (S_2) registered high available N (170.2 kg/ha), P (23.67 kg/ha) and K (202.5 kg/ha) in the soil after sesame harvest during the summer 2023 season. Similar results were observed in the subsequent kharif 2023 and summer 2024 seasons. Higher post-harvest nutrient availability might be due to poor weed management practices. Inadequate weed control likely increased competition for resources between weeds and crops, impairing effective nutrient uptake and resulting in elevated levels of accessible nutrients in the soil after harvest (28). Similar trends were observed in the subsequent kharif 2023 and summer 2024 seasons. This might imply that higher soil nutrient availability is associated with reduced plant uptake and yield, potentially due to luxury consumption or antagonistic effects between nutrients.

Irrespective of the crop growth stages, no interaction effect was found in post-harvest available nutrient status among M × S (establishment methods × weed management methods and harvesting methods) across any seasons.

Conclusion

The three-season study demonstrated notable variations in sesame seed and stalk yields, nutrient absorption and post-harvest soil nutrient availability attributable to the various crop establishment methods, weed management strategies and harvesting procedures assessed. Among the various establishment techniques, sesame manually sown in lines consistently outperformed other methods in terms of yields (seed and stalk) and nutrient uptake across all three seasons. Regarding weed management and harvesting, hand weeding at 30 DAS followed by either manual harvesting or using a reaper binder was superior in yields and nutrient absorption throughout the study. In terms of post-harvest soil nutrient levels, sesame sown using a pneumatic precision planter with non-pelleted seeds, regarding weed control through the application of Quizalofop ethyl at 20 DAS and manual harvesting, resulted in higher soil nutrient availability after sesame harvest. Hence, this study confirms that line sown sesame with hand weeding at 30 DAS either with manual harvest or using a reaper binder is the least strategy for enhancing sesame's nutrient uptake and yield.

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Authors' contributions

PM carried out the field experiment, and data analysis, and prepared the manuscript. TN guided in conducting the experiment, corrected the manuscript and provided assistance. HC monitored the experiment and assisted. RU provided necessary guidance on pelletization and sowing techniques. KR provided the necessary machinery and guidance for conducting experiment. BM made corrections to the manuscript. BR monitored the experiment. RS and RT helped in editing, summarizing and revising the 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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