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Sustainability of rice–sesame cropping systems: evaluating tillage and nutrient interactions in the eastern plateau and hills of the Indian sub-continent

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Precise information on the impact of varying soil tillage and nutrient levels on the performance of sesame cultivated after rice is lacking. Sesame is an edible oil-yielding industrial plant of global importance with high levels of unsaturated fatty acids, mainly oleic and linoleic, that demands defined tillage and fertilizer management for optimum productivity under rice fallow environments. While productivity under non-fallow agro-environments is a function of genotype and environment, under rice fallow, previous paddy management practices have an impact on the succeeding sesame crop in question. To better understand and manipulate the agroecology in the rice fallow culture, it is necessary to study the behavior of sesame cultivars in relation to the tillage requirements and macronutrient factors that influence productivity. Therefore, this study aimed to evaluate the productivity of rice fallow sesame in the eastern plateau and hills region (Odisha) of the Indian subcontinent as a function of tillage and nutrient management. Experiments conducted at Odisha University of Agriculture and Technology during 2019–2020 and 2020–2021 with tillage practices (reduced, conventional, and zero tillage) and fertilizer doses (control, 25% Recommended Dose of Fertiliser (RDF), 50% RDF, 75% RDF, and 100% RDF) indicated that the performance of rice fallow sesame was poor under zero till conditions as the sesame crop is poorly adapted to the rice fallow regime resulting in a yield penalty of up to 68%. Additionally, 75% RDF has yielded a statistically similar yield to that of 100% RDF for the rice fallow sesame. Furthermore, neither the oil content nor the fatty acid composition was modified by tillage and nutrient management practices.

KEYWORDS

sustainability, rice-based cropping system, rice fallow, rice–sesame, zero tillage, reduced tillage, conventional tillage, nutrient management

1 Introduction

Sesame, or benniseed (*Sesamum indicum* L., Pedaliaceae), is a versatile, short-duration (Oyeogbe et al., 2015), edible oilseed crop cultivated worldwide (Kumar et al., 2016; Harisudan and Vincent, 2019) in semi-arid and arid regions as a residual moisture crop (Pasala et al., 2021). It is often referred to as a small factory of potent molecules (Yadav et al., 2022) and is typically cultivated with limited resources (Dossa et al., 2023). Domesticated approximately 4,300 years ago (Wacal et al., 2024), the crop serves as a contingent crop, either during the *kharif* season or after rice harvest in several states of India. High productivity in this crop is largely dependent on tillage and nutrient management (Ramesh et al., 2021), as the physical soil structure is often deteriorated due to puddling in the preceding rice crop. Soil compaction caused by heavy machinery during rice cultivation may increase the soil's mechanical strength, adversely affecting the growth of the succeeding sesame crop (Chandrasekaran et al., 2024). While sesame can utilize residual nutrients from the preceding rice crop, a comprehensive nutrient management plan is essential. Unfortunately, rice fallow crops are rarely fertilized in the country (Ramesh et al., 2019) as these are typical residual moisture crops. However, the current crop management systems for rice fallow crops face challenges due to the rapid decline in soil moisture after rice harvest and/or prevailing low temperatures.

Rice fallow areas in different agroecological regions have diverse climates, soil types, and soil textures, based on which risk and uncertainties also vary. Bangladesh is characterized by a tropical climate, clay to clay loam soil with an estimated rice fallow area of 1.9 million hectares (Shahadat et al., 2019), which presents an opportunity for cropping intensification by cultivating a second crop during the dry season. Indonesia is yet another country where the rice and rice fallow areas are declining year by year (Hatta et al., 2023). The climatic condition of Odisha is characterized as sub–tropical hot and humid with red laterite soil type, sandy loam to coastal alluvial in texture (Panneerselvam et al., 2023). Drought, salinity, coupled with soil erosion, are the major uncertainties experienced in the Odisha region, which result in crop failure in the rice fallow period. Low moisture in the surface layer after harvest of rice leads to compaction and cracks in the prevalent Vertisols of the eastern plateau region (Mohapatra et al., 2022). Breaking the compactness through tillage may pulverize the soil for better establishment of sesame (Bahadar et al., 2007); however, in contrast, Alam et al. (2017) reported that tillage degrades soil structure, thereby resulting in low yield of rice succeeding crop (Jat et al., 2022). Sesame, being fine-seeded, requires fine tilth, although tillage would exhaust available residual soil moisture in the subsoil. Reduced tillage may be the option to break the compactness and to conserve the subsoil moisture to a certain extent. In this condition, Kar and Kumar (2009) reported that tillage after rice harvest creates clods with higher breaking strength and thus results in yield reduction due to restricted root growth.

To ensure high yield potential from rice fallow sesame crops, a thorough understanding of the soil's physical and chemical health within the paddy-upland cropping system (Zhou et al., 2014) is crucial. The productivity of rice fallow sesame remains low due to several management-related issues (Ramesh et al., 2019; Ramesh et al., 2020). Given that land remains fallow after rice harvest for various reasons, cultivating sesame with/without tillage is considered a climate-smart practice (Derpsch et al., 2014). Although sesame is a low nutrient-demanding crop, it still requires balanced fertilization (Ramesh et al., 2019). While studies have been conducted on nitrogen (Golan et al., 2022; Gebregergis et al., 2023; Berhane et al., 2024), phosphorus (Jat et al., 2020; Thanki et al., 2004), nitrogen–phosphorus (Singh et al., 1994; Thakur et al., 1998; Patra, 2001), and nitrogen–phosphorus–potassium (Shehu et al., 2010; Shehu, 2014), these studies have shown positive responses, but are limited for sesame following rice cultivation. The scarcity of research on tillage and nutrient management for the low productivity of rice fallow sesame highlights the need for further investigation.

An understanding of the processes that drive and determine the growth, establishment, and seed yield of crops under rice fallow conditions will allow for the development of economic and sustainable crop production systems in rice ecologies worldwide. However, the limited studies on sesame crops under rice fallow environments were inefficient, too few to establish a concrete relationship between tillage, crop yield, and/or nutrient management. Therefore, research on tillage requirements and nitrogen–phosphorus–potassium management for sesame crops following rice is essential to enhance the yield. The study hypothesizes that the sesame crop would require proper tillage before sowing to facilitate germination and stand establishment, and all major nutrients, *viz.,* N, P, and K, to get an optimum yield.

To address this research gap, field trials were conducted over 2 years at Orissa University of Agriculture and Technology, Dhenkanal, Odisha, in the predominant rice belt of India. The main objective was to determine the impact of tillage practices and nutrient management on the growth and yield of sesame. Insights from this study will ultimately help in developing comprehensive tillage recommendations for rice-fallow sesame in Odisha and similar rice-growing soil ecologies around the globe, enabling scaling up and broader application.

2 Materials and methods

2.1 Conducting the experiment

The experiments were conducted at the research farm of the All India Coordinated Research Project on Sesame, Regional Research and Technology Transfer Station (RRTTS), Mid Central Table Land Agro Climatic Zone of Odisha, Odisha University of Agriculture and Technology, Dhenkanal, Odisha, India (20° 37' N latitude and 85°36'E) longitude with an altitude of 328 feet above mean sea level (Dash et al., 2018), during March–May (first crop) and February–April (second crop) in 2020 and 2021, respectively. According to the ICAR agro-ecological subregions classification, the site falls under the sub-humid to humid eastern and southeastern uplands. As per Thornthwaite climate classification (Thornthwaite, 1948), the climate is hot, dry, and subhumid (C1) with microthermal characteristics (C1–C2), while the Köppen classification (Köppen, 1936), during the experiments, for the two cropping seasons are presented in Figures 1, 2. The soil type in the experimental area is classified as red sandy loams.

2.2 Experimental design and treatments

The experimental design followed a split-plot design with three replications. Tillage methods (reduced, conventional, and zero tillage) were assigned to the main plots, while nutrient management practices (control, 25% RDF, 50% RDF, 75% RDF, and 100% RDF; RDF: 50:30:20 kg NPK ha^{-1}) were applied to the subplots. Zero tillage is a conservation tillage practice where sesame seeds are directly sown into untilled soil after the harvest of rice without incorporating residues from previous rice crops and any field preparation. To impose the reduced tillage treatment, the cultivator was passed only once. In the conventional tillage (CT), a cultivator was used twice, followed by a rotavator once, to bring the soil to a fine tilth. The total experimental

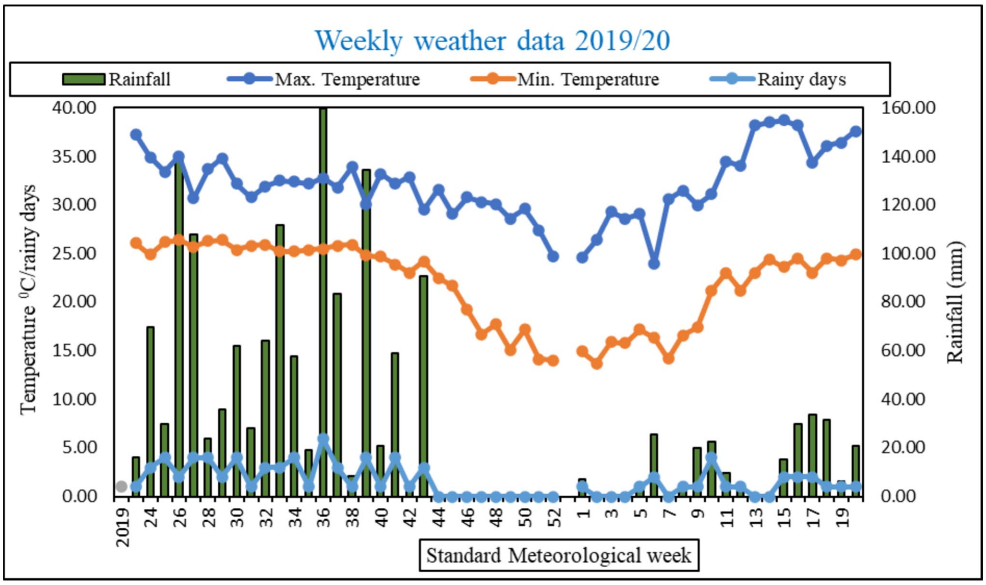

FIGURE 1
Meteorological data (2019/20) during the sesame growing period.

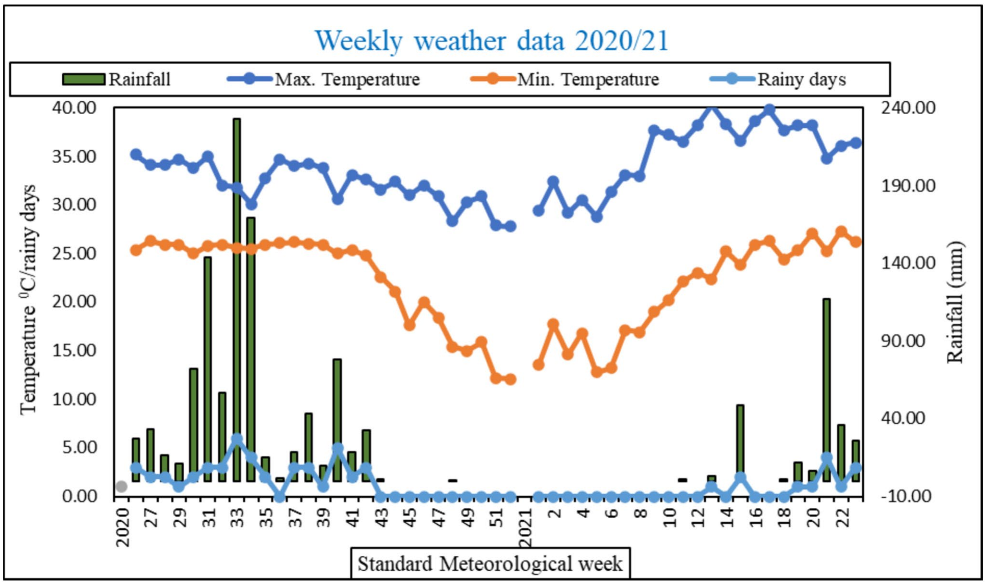

FIGURE 2
Meteorological data (2020–2021) during the sesame growing period.

area was 1,320 m^2, with each experimental plot comprising 10 rows of plants, covering 15 m^2 (5.0 × 3.0 m). Plant spacing used was 0.30 × 0.10 m with two plants per hole, resulting in 260 plants in the net harvest area (9.56 m^2) and a population of 2,71,967 plants ha^{-1}.

2.3 Experimental material

The detailed description of the crop varieties used in the study is given below. Pooja (CR-629-256) is a late-duration (150 days) short-height (90–95 cm) popular rice variety suitable for the shallow lowlands of states such as Odisha, Assam, Madhya Pradesh, and West Bengal. It has medium-slender grains, with field tolerance to major diseases and pests, and tolerance to water stagnation (up to 25 cm). It is suitable for late transplanting of aged seedlings. Smarak (OSC-560) is a sesame variety resistant (short and woody stem) to lodging, reaching a height of 120 cm and maturing in 80–85 days. The plant avoids shattering due to synchronous maturity, with visual cues for timely harvesting. It is suitable for *kharif* rainfed and summer irrigated conditions.

2.4 Experiment management

Rice (cv. Pooja) was sown in the nursery on 8 July 2019, transplanted on 3 August 2019, and harvested on 26 December 2019 during the first year. For the second year, the activities were conducted on 30 June 2020, 07 August 2020, and 04 December 2020. Fertilizer application is a standard practice of 80:40:40 kg N: P_2O_5:K_2O ha^{-1}. Phosphorus was applied as a basal dose, while N and K were applied in split doses. N was applied a split of 25% at transplanting, 50% at tillering, and 25% at the panicle initiation stage. K was parceled as 50% at transplanting and the rest at the panicle initiation stage. No micronutrient supplementation was done for the rice crop. After the rice harvest, the land remained undisturbed until sesame sowing. The first crop of sesame (cv. Smarak) was sown on 16 March 2020, and the second on 8 February 2021. Conventional and reduced tillage plots were sown using a trench hoe and rope, with fertilizer applied before soil covering. Zero tillage plots were sown by digging the soil with a trench hoe and applying fertilizers. After 10–15 days of emergence, thinning was performed, leaving one plant hole^{-1}. No irrigation was applied to the sesame crop as the crop received sufficient rain during the cropping season in the first year (2019/20), while three light irrigations were given in 2020/21 due to insufficient rainfall. The recommended blanket fertilizer dose was applied as per the recommendations for the state of Odisha for 100% RDF, while for other doses, amounts were decided by the treatment details. The source of N used was urea (N 46%), applied to the plots along with the fertilizer, in the amounts of 0, 12.5, 25, 37.5, and 50 kg ha^{-1}. A two dose-splitting procedure, *viz*., 50% at sowing and the rest at 30 days after sowing (DAS). In regards to P and K, full doses were applied at the time of sowing of sesame without a splitting procedure, *viz*., 0, 7.5, 15, 22.5, and 30 kg P_2O_5 ha^{-1} and 0, 5, 10, 15, and 20 kg K_2O kg ha^{-1} applied in the form of single super phosphate (P_2O_5 16%) and muriate of potash (K_2O 60%). Weeding and hoeing were carried out at 20 DAS to manage crop-weed competition to an acceptable level. Other crop management practices for biotic stresses were carried out as and when necessary, according to the recommendations.

2.5 Harvest and evaluated variables

Rice was harvested at physiological maturity (171 days), and seed yield was recorded at 12% seed moisture (data not reported). Sesame crop height (PH) was measured from the ground level to the tip of the plant at 30, 60 DAS, and at harvest. The number of branches plant^{-1} (NB) was counted at 30, 60, and harvest. Harvesting of the first and second sesame crops was carried out at 100 and 103 DAS, following which the following traits were evaluated: number of branches plant^{-1}; no of capsules plant^{-1} (NC); biomass yield; seed yield; harvest index; 1,000-seed weight; oil content, and fatty acid composition. Seed yield was determined from the net plot area at 12% seed moisture.

2.6 Oil content

Oil content was analyzed using a benchtop pulsed nuclear magnetic resonance (NMR) analyzer (Oxford-MQC-5, London, United Kingdom), calibrated with known oil samples. Calibration was performed with a 40 mm diameter sample probe at 5 MHz operating frequency, 4 scans, 1 s recycle delay, and 40.00 magnetic box temperature. The NMR room temperature was maintained at 25°C ± 2. Before the construction of the calibration sample, seeds were dried by keeping them at 80°C for 8 h in a hot air oven (Yadav and Murthy, 2016).

2.7 Fatty acid profiling

Oil was extracted using hexane in a Soxhlet apparatus (Extraction unit, E-816, Buchi, Flawil, Switzerland), and transesterified using 2 mL of 13% methanolic KOH for 30 min at 55°C. The organic phase was extracted with hexane and washed with water till neutral pH. The hexane was dried over anhydrous sodium sulfate and concentrated with nitrogen to get methyl esters. Fatty acid composition was determined using an Agilent 7890B gas chromatograph (Santa Clara, CA, United States) equipped with a flame ionization detector (FID) and an autosampler. Peak separation was performed on a DB-225 capillary column (diameter—320 μm, length—30 m, film thickness—0.25 μm) from Agilent Technologies. The carrier gas was nitrogen set to a constant gas flow of 1.2 mL/min at 150°C initial temperature. Then 0.2 μL of the sample was injected at a 20:1 split ratio into the column with the following temperature conditions: 150°C for 2 min; raised from 150 to 300°C at 10°C/min. Both the inlet and the detector were set to 325°C. The fatty acid composition was determined based on relative peak area using EZChrom Elite Software (Anjani and Yadav, 2022).

2.8 Statistical analysis

The data for all collected variables were subjected to analysis of variance (ANOVA) for the split-plot design using SAS version 9.2. Treatment means were tested for significance using critical difference (CD) at a 5% probability level.

3 Results and discussion

3.1 Environmental conditions and crop development

The mean minimum atmospheric temperature conditions during both years were nearly similar, though 2020/21 was slightly warmer than 2019/20, as evident from the mean maximum temperature recorded during the 23rd Meteorological Standard Week (MSW) of the first year (2019/20) (Figure 1) and the 26th MSW of the second year (2020/21) (Figure 2).

Total precipitation in 2020/21 was greater than in 2019/20. While the precipitation during the first year (2020) was adequate for sesame production, in-season rainfall variability in the second year (2021) necessitated supplemental irrigation to avoid moisture stress and potential yield reduction.

Despite variations in meteorological conditions, physiological maturity of the cultivar was reached at 100–103 DAS during both years. The sesame cultivar progressed through normal growth phases and stages at the same time, in both years, with slight changes in the harvest date due to management practices, despite a 19-day difference in sowing dates in the second year.

3.2 Progressive plant height increments

For PH, a significant interaction between tillage and fertilizer dose was observed in both crops starting from 60 DAS, while in the second crop, the interaction was significant even at 30 DAS. It was observed that as the RDF rate increased, PH also increased due to the higher availability of nutrients (N, P, and K) that were absorbed by the plants. However, the plants were shorter in the second year. The tallest plants had heights of 118 and 100 cm in conventional tillage systems (Table 1) during the first and second years, respectively. Under 100% RDF, the tallest plants were recorded reaching 126 and 100 cm in the first and second years, respectively. Suboptimal doses of nutrients (25–75% RDF) resulted in insignificantly shorter plants, indicating that nutrients do contribute to source development rather than enhancing plant height (PH). The higher soil nutritional status maintained by adequate NPK rates contributed to increased PH.

In PH, there was an interaction between tillage and fertilizer dose in both crops from 60 DAS, while in the second crop, even 30 DAS showed a significant interaction, where it was observed that, as the RDF rate increased, an increase in PH occurred. This increase occurred due to the higher availability of nutrients (N, P, and K) to the sesame plants that were consequently absorbed from the soil. It was observed that different rates of NPK might have maintained a higher soil nutritional status for the sesame crop.

3.3 Progressive branch growth increments

In branch growth (NB), there was an interaction between tillage and fertilizer dose in both crops, except at 30 DAS. As the RDF rate increased, more branches developed. This increase occurred due to the proportionate combined higher availability of nutrients (N, P, and K) to the sesame plants, which were consequently absorbed from the soil. However, the branching was very little as compared to the second year (2021), except for zero tillage management in the first year (2020). Highly branched sesame plants were observed, *viz*., 3.6 and 3.8 plant^{-1} under the conventional tillage in the first year and under zero tillage in the second year, respectively. Regarding nutrient management, 100% RDF had the maximum number of branches plant^{-1}, with values of 4.02 and 3.72 for the first and second years, respectively, and all suboptimal doses of nutrients proved to be inferior (Table 2).

Phenological observations indicated that CT facilitated earlier branch development in both years, continuing up to the harvest stage. However, there were no significant differences in the year 2020 at 30 DAS. These responses were related to the root development of sesame, which requires soil aeration and nutrients, intrinsically linked to tillage operations. Bahadar et al. (2007) noted improved porosity enhances soil aeration and oxygen availability. Although the photosynthetic capacity of sesame stems remains unknown (Couch et al., 2017).

3.4 Number of capsules per plant

For NC, a correlation was observed between increased RDF rates and NC. The maximum NC values were recorded at 100% RDF for both years. However, NC values were higher in 2020 than in 2021. Temporal variations were noted in sesame crops concerning tillage and nutrient responses, particularly in plants without fertilization (0 kg ha^{-1} NPK) or with 100% RDF. Sesame yield components include the number of plants per unit area, the number of branches per plant, the number of capsules (NC) per leaf axil, the number of seeds per capsule, and the seed weight (Delgado and Yermanos, 1975). To pinpoint the most important factor that determines high sesame yield, we analyzed the number of capsules plant^{-1} in different treatments. In NC, it was observed that as the RDF rate increased, so did NC. The maximum values were obtained at 100% RDF in a year. However, there were more NC values obtained during 2019/20 than in 2020/21. One of the important ways of increasing seed yield is sesame with an extra number of

TABLE 1 Plant height increments during 2020 and 2021.

Treatment	2020			2021		
	30 DAS	60 DAS	Harvest	30–60	60 DAS	Harvest
Tillage practices						
Reduced tillage	25.40	81.97	113.25	23.43	64.64	94.40
Conventional tillage	26.08	84.84	118.99	24.85	69.93	100.84
Zero tillage	24.37	68.77	97.13	21.07	50.83	79.59
CD (p = 0.05)	0.61	1.86	2.93	0.58	2.09	1.51
Fertilizer dose						
Control	25.00	60.53	93.40	22.49	51.04	83.96
25% RDF	24.83	69.84	102.93	22.18	56.71	86.62
50% RDF	25.31	76.53	107.53	23.16	59.96	90.82
75% RDF	25.40	88.00	118.78	23.62	65.82	96.11
100% RDF	25.87	97.73	126.31	24.13	75.47	100.53
CD (P = 0.05)	0.63	2.00	2.75	0.35	1.36	1.34

Interaction was significant. DAS: Days after sowing.

TABLE 2 Branch increments during 2020 and 2021.

Particulars	2020			2021		
	30DAS	60DAS	Harvest	30DAS	60DAS	Harvest
Tillage practices						
Reduced tillage	1.01	3.20a	3.37a	1.03	2.86c	3.02c
Conventional tillage	1.04	3.37a	3.60a	1.04	3.71a	3.80a
Zero tillage	1.00	2.97b	3.16b	1.00	3.14b	3.23b
CD ($P = 0.05$)	NS	0.18	0.25	0.03	0.07	0.05
Fertilizer dose						
Control	1.00	2.76	2.89e	1.00	2.89	3.00e
25% RDF	1.00	2.96	3.07d	1.02	3.14	3.22d
50% RDF	1.02	3.02	3.31c	1.02	3.20c	3.36b
75% RDF	1.04	3.40	3.60b	1.02	3.36b	3.46b
100% RDF	1.02	3.78	4.02a	1.04	3.60a	3.72a
CD ($P = 0.05$)	NS	0.16	0.15	NS	0.14	0.10

Interaction was not significant.

capsules per leaf axil (Baydar et al., 1999) and so a greater number of capsules plant^{-1} in turn. According to our data, the main yield-attributing character of sesame seems to be the number of capsules plant^{-1} as reported by Baydar (2005).

Theoretically, if plants provide a higher number of capsules per plant, more capsules per unit of urea are then acquired, and consequently, more seed yield might be provided. Thus, the sesame plant architecture plays an important role in the final seed yield (Gadri et al., 2019), which is mediated by tillage and nutrient management in our study. The behavior of NC indicated that an increased rate of RDF, providing greater availability of N, P, and K in the soil, allowed greater translocation of nutrients to the sesame plants, remobilized into the capsules, consequently might have promoted an increase in the productivity of the sesame. Differences in NC can influence seed number and size too. In the sesame crops, there were temporal variations in tillage and nutrient response, either in the absence of fertilization (0 kg ha^{-1} NPK) or 100% RDF.

3.5 Seed yield

Tillage and cropping systems have complex effects on soil quality, viz., physical, chemical, and biological properties (Kladivko, 2001), and the rice–sesame cropping system is no exception. Recently, Yunyan et al. (2023) reported that a decrease in temperature hampered root length, shoot length, and fresh weight of sesame at the early seedling stage, with a significant effect at 18°C. In the current study, the minimum temperature during 1 MSW was 13.2°C, and in the subsequent week, it increased to 17.7°C during 2020/21, which might have interfered with the root system architecture of sesame to reduce the seed yield as compared to the 2019/20 season, wherein the minimum temperature was not lower than 21.2°C. Among the tillage methods, conventional tillage, i.e., two times tillage followed by bringing the soil to fine tilth, resulted in higher yields compared to reduced or zero tillage in the rice fallow sesame system.

Seed yield was higher in the first crop (Table 3), probably due to climatic variables, such as temperature, relative humidity, and rainfall, affecting sesame agronomic performance. Currently, there is not a great deal of information available in regard to the temperature response of sesame.

Tillage and cropping systems have complex effects on soil quality, *viz.*, physical, chemical, and biological properties (Kladivko, 2001). Recently, Yunyan et al. (2023) found that a decrease in temperature hampered root and shoot length and fresh weight of sesame during the early seedling stage, with significant effects at 18°C. In the current study, minimum temperatures during the year 2020/21 were (1 MSW) was lower 13.2°C to 17.7°C, than during 2019/20 potentially reducing crop yield through root system architecture of sesame to reduce the seed yield, wherein the minimum temperature was not lower than 21.2°C.

High temperatures were not experienced in either year (maximum temperatures were 38.7°C at 15 MSW and 40.3°C at 13 MSW during 2019/20 and 2020/21, respectively). However, low temperatures can delay maturation in warm-season plant species such as sesame, reducing yields (Baath et al., 2020; Baath et al., 2021). Temperature is one of the major climatic factors that has a direct influence on sesame growth. The average temperature during the sesame growing season was 30.4°C and 29.6°C in 2019/20 and 2020/21, respectively. Fageria (1998) reported a temperature of approximately 27°C as ideal for the cultivation of sesame. In the current study, 30°C yielded a higher yield than 29°C, indicating the higher heat unit requirement of sesame for optimizing sesame yield. The findings of this study are in good agreement with those obtained by Fageria (1998), who also reported that these climatic variables are likely to influence NPK fertilization efficiency and tillage to determine the yield capacity of any plant.

Among tillage methods, conventional tillage (two times tillage followed by bringing fine tilth preparation) resulted in higher yields than reduced tillage or zero tillage for rice fallow sesame. Zero tillage could invariably have competitive weed pressure since reduced water availability and/or entry would alter the competitive balance between crops and weed species, intensifying the crop-weed competition pressure (Ramesh et al., 2017). Intensive tillage for rice creates

TABLE 3 Sesame yield and yield attributing characters as influenced by tillage and fertilizer doses under rice fallow ecologies.

Treatment	No of capsules plant^{-1}		Productivity (kg ha^{-1})		Biomass (kg ha^{-1})		Harvest index	
	2020	2021	2020	2021	2020	2021	2020	2021
Tillage practices								
Reduced tillage	47.25	38.94	441	390	1,595	1,399	27.55	27.57
Conventional tillage	53.33	43.49	462	419	1778	1,494	27.55	28.02
Zero tillage	34.11	33.85	349	219	1,332	798	26.15	27.50
CD (P = 0.05)	1.85	1.28	65	67.4	25.08	14	0.31	0.23
Fertilizer dose								
Control	33.62	31.92	322	266	1,224	967	26.29	27.61
25% RDF	37.11	33.73	353	283	1,319	1,033	26.71	27.34
50% RDF	45.22	38.79	379	328	1,580	1,192	27.01	27.45
75% RDF	51.27	42.91	489	393	1763	1,373	27.65	28.00
100% RDF	57.27	46.44	544	444	1955	1,588	27.74	28.08
CD (P = 0.05)	1.64	1.12	65	63.3	19.46	18.64	0.20	0.25

Interaction was not significant.

hardpans in the subsoil (Ogunremi et al., 1986), which must be broken for sesame establishment. Although no-tillage ensures sustainable cropping intensification (Derpsch et al., 2014) through preservation of soil quality (Lal, 2001), the requirements of the sesame crop could not be met through zero-tillage regimes. Sesame crop stand establishment is considered very important for sesame production, which is in jeopardy when tillage is foregone or kept at the minimum scale. In the initial two fortnights after sowing, sesame exhibits a relatively deferred aboveground biomass development (Amare, 2011) to an extent of 35 DAS (Ribeiro et al., 2018), particularly mastered by tillage regimes. The crop is not as plastic as that of the popular wheat crop in a rice–wheat cropping system wherein wheat is quite plastic and is expected to compensate for low plant populations through additional tillers depending on environmental conditions (Dahlke et al., 1993; Tilley et al., 2019). Moreover, the sesame crop's early root development and proliferation are expected to be controlled by soil fertility and genotypic factors when soil fertility is poor (Gloaguen et al., 2022). Our results conform with the findings of Uzun et al. (2012), reporting that despite higher energy savings and lower land preparation costs due to no-till for sesame, there was a yield penalty too. To promote sustainable production, lower energy consumption, with maximum energy use efficiency, is essential for any system (Rahil et al., 2024).

It has been unclear whether the low yields of crops following rice paddies were due to rice paddies (Fageria et al., 2011) altering soil physical or mineral characteristics, or both (Yang et al., 2022). Although paddy-upland rotation may increase microbial diversity (Hou et al., 2018), the productivity of rice fallow sesame under zero-till conditions is poor due to poor adaptation (Harisudan and Sapre, 2019). Probably, soil pressure under zero till is a constraint to sesame since a soil pressure of at least 1.1 kg/cm^2 is beneficial for sesame production (Gabrillides and Akritidis, 1970).

It is beyond doubt that sesame is well adapted to nutrient-starved soil environments, and thus, in practice, fertilization is infrequent, whether organic or inorganic fertilizers, and sole or rice fallow crop. Furthermore, the crop management practices and interactions among the soil physical and chemical factors have an astounding effect on the productivity as well as the use efficiency of the applied nutrients. Nitrogen becomes a limiting nutrient, since sesame is sown in rice fallows; the crop is seldom supplied with nutrients (Ramesh et al., 2019), more than any other nutrient (Bredemeier and Mundstock, 2000), at times may reduce oil content too in sunflower (Biscaro et al., 2008). The literature lacks solid fertilization recommendations or guidelines for a rice fallow sesame crop, yet there is much evidence to illustrate marginal yield gains to N under field conditions (Zenawi and Mizan, 2019). Besides, phosphorus availability to plants grown in recently flooded soils was reported ostensibly due to an increase in phosphorus sorption from freshly oxidized iron oxides and hydroxides that were reported during the early 70s (Willett, 1979) and confirmed by Heritage (1982). As such, the waterlogged condition in rice increases water-soluble and exchangeable iron due to a decrease in redox potential (Gotoh and Patrick, 1974). Hence, a graded increase in fertilizer dose has improved soil nutrient availability and higher sesame yield. Despite being a critical ingredient to crop yield, the analysis undertaken in this study indicates that just a 75% RDF can result in significant equal effects on crop yield to that of 100%. The extent of the response rivaled that with 75% RDF application to the highest recorded yield under 100% RDF. Our data show that both the capacity for and the efficiency of rice fallow sesame production are greater for the combined application of N, P, and K, indicating a highly specialized requirement for the nutrients that has not hitherto been recognized for sesame production. The soils of the experimental site were sandy loam with 240:17:530 kg NPK ha^{-1}. It is expected that tillage practices and fertilizer management might interact in getting higher sesame yield, subject to water availability, which warrants further study. Higher yields obtained with 100% NPK might be due to the availability of sufficient nutrients in the soil, while no fertilization would result in nutrient mining in rice–fallow systems, as reflected in sesame yield in the current study. The same was witnessed in the study of Chandrasekaran et al. (2024). Given the potential importance of tillage and nutrient application to the enhancement of sesame yield, we propose the following strategy to capitalize on the high capacity of the rice–sesame cropping system for realizing the optimal yield potential. This is where we make the central point that only appropriate land management practices, coupled with nutrient management, would ensure higher crop yields in rice–fallow sesame as well, although tillage systems are location-specific.

3.6 Sesame oil and fatty acid composition

The oil content of sesame was unaffected by tillage practices or nutrient doses in the present study (Table 4). The fatty acid composition is one of the prime indicators of the nutritional value of sesame oil (Gharby et al., 2017), as the oil belongs to the oleic–linoleic acid group (Hassan, 2012). The results showed 14.3–15.4% saturated fatty acids and 82.2–86.3% unsaturated fatty acids. Among the unsaturated fatty acids, oleic acid, a monounsaturated omega-9 fatty acid (43.5–45.1%), was the dominant fatty acid, followed by linoleic acid (C18:2, omega-6 Fas; 38.7–41.2%). On the other hand, palmitic acid (9.6–10.0%) was the dominant fatty acid, followed by stearic acid (5.3–5.4%) among the saturated fatty acids. Generally, the oil content of sesame and its composition (Ali et al., 2016), are expected to be influenced by soil nutrient supply particularly N, P, and K, besides secondary nutrients, viz., Ca and Mg, since plants synthesize a huge variety of fatty acids *de novo* from precursors derived from photosynthates, for example. Oleic acid and linoleic acid are the two major fatty acids in sesame oil, constituting approximately 85% of the total fatty acids (Dar et al., 2019). Nitrogen is generally required for the synthesis of fat, which requires both N and carbon skeletons during seed development (Patil et al., 1996). Bellaloui et al. (2018) and Ali et al. (2016) reported an increase in the concentration of linoleic acid when soil was supplied with adequate soil N, besides an adequate supply of soil P and K (Aytac et al., 2017). Therefore, maintaining adequate supplies of these macronutrients in the soil would improve crop productivity and quality. Wacal et al. (2019) noticed a change in sesame oil fatty acid composition when sesame was monocropped in Japan. However, in the current study, since sesame is rotated with rice, the deleterious effects of monocropping might have been nullified, and the treatment variables could not provide any effect on the fatty acid composition of sesame. Our results conform to the findings of Priya et al. (2022), who reported only insignificant changes in sesame fatty acid composition due to tillage and fertilizer management.

3.7 Economic analysis

The economic analysis is of utmost importance as the technology developed is viable not only based on the superiority in yield but also on the profitability (Harisudan et al., 2023) important in recommending a technology. The total cost of rice fallow sesame cultivation under conventional tillage is high (291 USD); however, the production cost per kg of seed produced is less, and profitability is high compared to other tillage practices. Zero tillage fetches a lower cost of production (259 USD), but the production cost per kg of seed produced is high, and profitability is very low compared to other tillage practices. With respect to fertilizer dose, application of 100% RDF requires a higher cost of cultivation (302 USD); however, production cost per kg of seed produced is less, and profitability is high compared to a lower dose of fertilizer. The use of fertilizer will reduce the production risk by increasing productivity and profitability (Adem, 2024).

Higher gross returns, net returns, and benefit–cost ratio were realized in conventional tillage since higher seed yield was obtained under conventional tillage. Sesame under zero tillage produced low seed yield, which resulted in a low gross return, net return, and benefit–cost ratio. Among the fertilizer doses, the application of 100% RDF recorded higher gross returns, net returns, and benefit–cost ratio. The results of higher returns at higher doses of fertilizer agree with those reported by Zebene and Negash (2022). Low fertility results in less seed yield, resulting in a low gross income, net return, and benefit–cost ratio. Similar results of low productivity at low fertility dose were observed by Ramesh et al. (2021). Among pulses, lentil

TABLE 4 Sesame seed oil content and fatty acid composition as influenced by tillage practices and fertilizer management.

Treatment	Oil content (%)		Palmitic acid		Stearic acid		Oleic acid		Linoleic acid	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Tillage practices										
Reduced tillage	43.7	43.6	10.1	9.9	5.4	5.4	45.5	45.4	38.7	38.8
Conventional tillage	43.8	43.8	9.9	10.0	5.3	5.3	44.4	44.5	40.2	40.1
Zero tillage	43.5	43.4	9.9	10.0	5.3	5.3	44.2	44.3	40.3	40.3
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer dose										
Control	44.1	44.2	9.6	9.6	5.3	5.3	43.8	43.9	41.1	41.2
25% RDF	43.6	43.5	10.2	10.2	5.4	5.3	45.4	45.5	38.8	38.9
50% RDF	43.3	43.5	10.3	10.3	5.5	5.4	44.9	44.8	39.0	39.3
75% RDF	44.1	44.2	9.8	9.8	5.3	5.3	44.2	44.3	40.5	40.6
100% RDF	43.2	43.3	10.0	10.0	5.2	5.3	45.1	45.1	39.4	39.6
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

(*Lens culinaris* Medik.) in Nepal and South Asia is typically sown after rice in annual cropping rotation, where there is demand for lentil as a typical pulse crop, and application of a recommended dose of fertilizers/compost is recommended (Ghimire et al., 2023) for optimum yields. This system also needs proper fertilization, similar to our findings for sesame in the state of Odisha, India.

4 Conclusion

Encouraging sesame as a promising succeeding crop to *kharif/rabi* rice with appropriate tillage is critical. Despite advancements in linking tillage and nutrient management for rice fallow sesame, significant gaps remain in educating farmers on finer-scale crop and nutrient management practices, as this is soil-specific. Rice fallow sesame requires soil disturbances and at least three-fourths of the general recommended fertilizer dose to optimize productivity. This result differed from the conventional cultivation of rice fallow crops by assuming that the residual nutrients from rice could enhance the sesame yield through his perception of rice fallow pulse crop management strategies. In the second part of the statement, we would reverse the equation, that nutrient management is an absolute need for rice fallow sesame crops. One somewhat unexpected finding was that 75 and 100% RDF yielded statistically similar yields. This study highlights the necessity of appropriate tillage/land and nutrient management practices to maximize sesame yields in rice–fallow systems. Further research is needed to address soil physical property constraints to enhance productivity.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KR: Project administration, Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. CH: Writing – review & editing. BD: Investigation, Writing – review & editing. KVR: Writing – review & editing. AQ: Writing – review & editing. PY: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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