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RESEARCH ARTICLE

Performance of foxtail millet (*Setaria italica* (L.) P. Beauv.) based cropping system for rainfed agro ecosystems in Semi-Arid Tropics of India

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Abstract

A field experiment was conducted during the *Kharif* seasons of 2020, 2021 and 2022 at the Centre of Excellence in Millets, Athiyandal, Thiruvannamalai, Tamil Nadu, to investigate the performance of foxtail millet (*Setaria italica* L.) based cropping system for rainfed agro- ecosystems in the north-eastern agro climatic zone of Tamil Nadu, India. The experiment was laid out in a randomized block design (RBD) with 7 treatments, *viz*., T_1: Sole foxtail millet; T_2: Foxtail millet + Groundnut (*Arachis hypogea* L.) (4:1); T_3: Foxtail millet + Groundnut (*Arachis hypogea* L.) (6:1); T_4: Foxtail millet + Sesame (*Sesamum indicum* L.) (4:1); T_5: Foxtail millet + Sesame (*Sesamum indicum* L.) (6:1); T_6: Foxtail millet + Niger (*Guizotia abyssinica* (L.f.) Cass) (4:1); T_7: Foxtail millet + Niger (*Guizotia abyssinica* (L.f.) Cass) (6:1). Each treatment was replicated three times . High- quality seeds with a high germination percentage, uniform size and freedom from pests, diseases and weed seeds were used for the experiment *viz*., foxtail millet (ATL 1), groundnut (VRI 8), sesame (TMV 7) and niger (JNS 28). The results revealed that the foxtail millet and sesame intercropping system in a 4:1 ratio exhibited the highest foxtail millet equivalent yield (2266 kg/ha) along with notable relative production efficiency (10.5%) and relative economic efficiency (18.1%). This study emphasizes the potential for expanding foxtail millet cultivation by integrating intercropping with oilseed crops, thereby contributing to both the area and production of foxtail millet.

Keywords

competition functions; foxtail millet; intercropping; oilseed crops; yield attributes

Introduction

Rainfed agriculture plays a key role in global agricultural systems, especially in regions with limited irrigation facilities or scarce water resources (1). However, farmers in rainfed areas face several problems, including unpredictable weather patterns (2), which significantly pose challenges to improving crop yields (3), farmers' income, livelihoods and food security. Addressing these challenges requires innovative approaches, including diversifying cropping systems with climate-resilient and nutritionally rich crops (4).

Millets, in particular, emerge as a promising solution due to their adaptability and resilience. As climate-resilient crops (5), millets can thrive under a wide range of environmental conditions with minimal water requirements. They exhibit enhanced growth and productivity even in nutrient-deprived soils, reducing dependency on inorganic fertilizers and lowering susceptibility to environmental and ecological stresses (6). Additionally, millets contribute to increased carbon sequestration, making them an environmentally sustainable choice. These resilient crops have served as staple food for numerous communities for centuries and are now recognized as Nutri-cereals for their superior grain nutritive qualities (7), particularly their high levels of calcium, iron,and zinc. Moreover, millets are rich in vitamins, dietary fibers, amino acids, storage proteins and various bioactive compounds (8), offering 7-12% protein, 75-85% carbohydrates, 1-4% fat, 2-3% minerals and abundant phytochemicals (9).

India ranks first among the world's rainfed agricultural nations in terms of both quantity and quality of its output, as reported by the National Rainfed Area Authority. Rainfed agriculture contributes approximately 40% of the nation's food production. These regions receive annual rainfall ranging from 400 to 1000 mm, which is highly unpredictable, irregular and unevenly distributed. Consequently, a notable declines in food output are frequently observed. Climate change has the most significant influence on rainfed agriculture (10, 11).

Foxtail millet (*Setaria italica* L.) is a cereal crop that has been cultivated for centuries in Asia and Africa (12). Despite its significant nutritional benefits and adaptability to various agro -climatic conditions, its cultivation remains relatively less than major staple crops due to its lower yield potential (13). However, foxtail millet holds great promise for the future, as it exhibits characteristics that support sustainable and resilient agricultural practices (14, 15).

Renowned for its exceptional drought tolerance (16, 17), it thrives in water-scarce regions, making it a crucial crop for addressing climate change challenges. Additionally, its rich nutritional profile (18), low input requirements (19) and resilience to climate variability enhance its role in promoting diverse diets, cost-effective farming and climate-resilient agriculture. It also offers potential for intercropping, biofuel production and soil erosion control (20), thereby contributing to sustainable agricultural landscapes.

An agricultural practice called intercropping involves growing two or more crops simultaneously in close proximity on the same piece of land (21). It is primarily aimed at maximizing yield from a given land area by optimizing resource use. Intercropping provides numerous advantages, including increased profitability (22, 23), improved land use efficiency and protection of main crops. It also help mitigate environmental issues such as soil erosion and pest infestations. By integrating crops with different root structures, intercropping enhances ground cover and soil stability, preventing soil erosion and crust formation (24).

In addition, certain intercropping combinations, such as legumes with cereals, contribute to soil fertility by fixing atmospheric nitrogen, reducing the need for chemical fertilizers (25). This practice also acts as a natural pest deterrent, for example, planting pest-repellent crops like marigold alongside vegetables can disrupt pest breeding cycles and protect the main crop. In addition, intercropping suppresses weed growth by maximizing ground coverage, conserves resources and space and ensures stable yields even if the main crop underperforms. It also fosters nutrient sharing among neighboring plants (26), creating a more sustainable and resilient farming system.

In the traditional crop cultivation, farmers typically do not implement strategic spatial arrangements when practicing intercropping. This lack of spatial planning can result in suboptimal yields compared to well-planned intercropping systems. In the traditional method, crops are often cultivated without fully taking advantage of the synergies that arise from the deliberate arrangement of different plant species within the same agricultural space.

Spatial arrangements in intercropping involves the intentional placement of crops relative to one another, considering factors such as plant height, growth rates, nutrient requirements and resource utilization (27). Neglecting these spatial considerations can lead to inefficient resource use, increased competition for nutrients and sunlight and a higher likelihood of pest and disease proliferation (28). Efficient intercropping enhances soil nutrient utilization, (29). Additionally, intercropping with small millets in dryland area serves the dual purpose of conserving soil health, curbing water runoff (30) and improving soil fertility (31).

Global millet production reached 30.1 million tonnes in 2021 (32). India, which leads millet production in the region, cultivates small millets on approximately 6.8 lakh ha, accounting for nearly 80% of Asia's total millet output (33). Small millets contribute 41% of the overall output within a cultivated area of approximately 7.0 lakh ha, with a productivity rate of 633 kg/ha (34) as a rainfed crop (Fig.1.). In Tamil Nadu, foxtail millet is predominantly sown as a sole crop in june-july, with occasional sowings observed from september to october (35). The major millets-growing districts in Tamil Nadu are Vellore, Dharmapuri, Krishnagiri and Tiruvanamalai.

With the primary objective of maximizing the production of the main crop, intercropping serves as a strategic approach to enhance overall system productivity by effectively using the resources at hand (36) and suppressing weed growth (37). To explore these benifits, an experiment was planned to develop an optimal intercropping and sequential cropping system for foxtail millet (*Setaria italica* L.) under rainfed conditions. The spatial

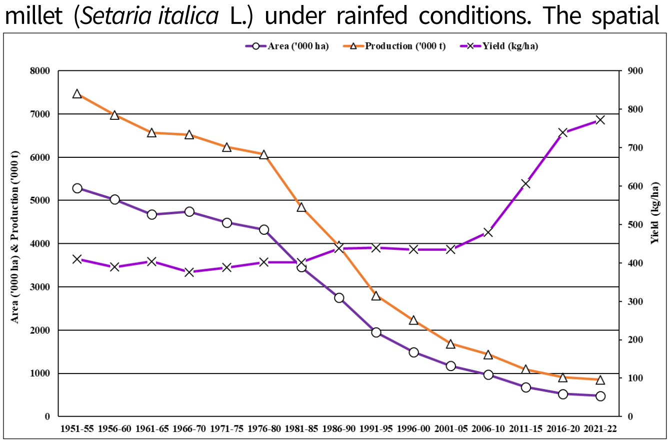

Fig. 1. Area, production and productivity of small millets in India from 1951-55 to 2021-22.

arrangements were chosen based on their ability to balance competition and complementarity between crops, optimizing resource utilization such as light, water and nutrients.

By embracing and implementing strategic spatial arrangements in intercropping, farmers can unlock the potential for increased crop yields, improved resource utilization efficiency (38) and overall sustainability in agriculture. Drawing upon insights from prior studies, the present research was formulated to explore the growth and yield potential of foxtail millet when intercropped with oilseeds. Additionally, the study aimed to evaluate the economic aspects of system productivity and assess soil health under rainfed conditions.

Materials and Methods

The present study was conducted during the rainy (*kharif*) season of 2020, 2021 and 2022 at Centre of Excellence in Millets (12° 07' N latitude; 78°99' E and 163.36 m MSL altitude), Athiyandal, Thiruvanamalai, Tamil Nadu (Fig.2.). Prior to the experiment, the land had been used for the cultivation of various small millet crops over the past 8 years, following standard agricultural practices consistently.

One of the major challenges faced during the study was rainfall variability across the three years, which significantly impacted crop performance and results. It was addressed by analyzing long-term rainfall patterns. The amount of rainfall received during the cropping period is depicted in Fig.3. The general climatic conditions of the experimental location included a maximum temperature of 36°C and a minimum temperature of 18°C, with relative humidity ranging from 67% to 86%. Soil analysis revealed that the texture of the soil was sandy clay loam, with a pH of 7.2. The soil had low available nitrogen (137.0 kg ha^{-1}), high available phosphorus (32.1 kg ha^{-1}) and medium available potassium (141.0 kg ha^{-1}).

The experiment was designed using a randomized block design (RBD) with 7 treatments, each replicated three times. The treatments were as follows: T_1: Sole foxtail millet; T_2: Foxtail millet + Groundnut (*Arachis hypogea* L.) (4:1); T_3: Foxtail millet + Groundnut (*Arachis hypogea* L.) (6:1); T_4: Foxtail millet + Sesame (*Sesamum indicum* L.) (4:1); T_5: Foxtail millet + Sesame (*Sesamum indicum* L.) (6:1); T_6: Foxtail millet + Niger (*Guizotia abyssinica* (L.f.) Cass) (4:1); T_7: Foxtail millet + Niger (*Guizotia abyssinica* (L.f.) Cass) (6:1). Grain and straw yields were recorded for all treatments. High-quality seeds of foxtail millet (ATL 1), groundnut (VRI 8), sesame (TMV 7) and niger (JNS 28) were used, sourced from Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu.

The experimental field was thoroughly plowed using a tractor-drawn disc plow, followed by harrowing and leveling. Once a fine tilth was achieved, the field was divided into small plots with bunds formed manually. A basal application of farmyard manure (12.5 t/ha) was uniformly spread across the entire experimental field during the final plowing. The high- quality seeds of foxtail millet, along with intercrop seeds, were sown immediately after field preparation under rainfed conditions. A basal application of 44:22:0 kg NPK/ha was uniformly applied to all sowing for the foxtail millet base crop.

Germination of foxtail millet seeds was observed by the third day after sowing. Gap filling and thinning activities were undertaken in both base and intercrops on the 10th day after sowing to ensure an optimal plant

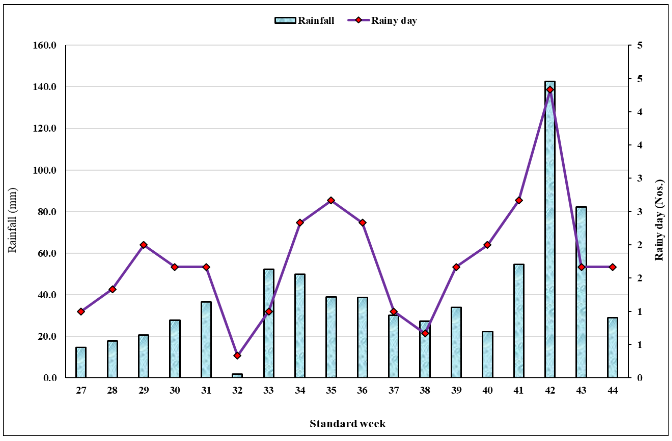

Fig. 3. Average rainfall and rainy days (3 years) during the cropping period.

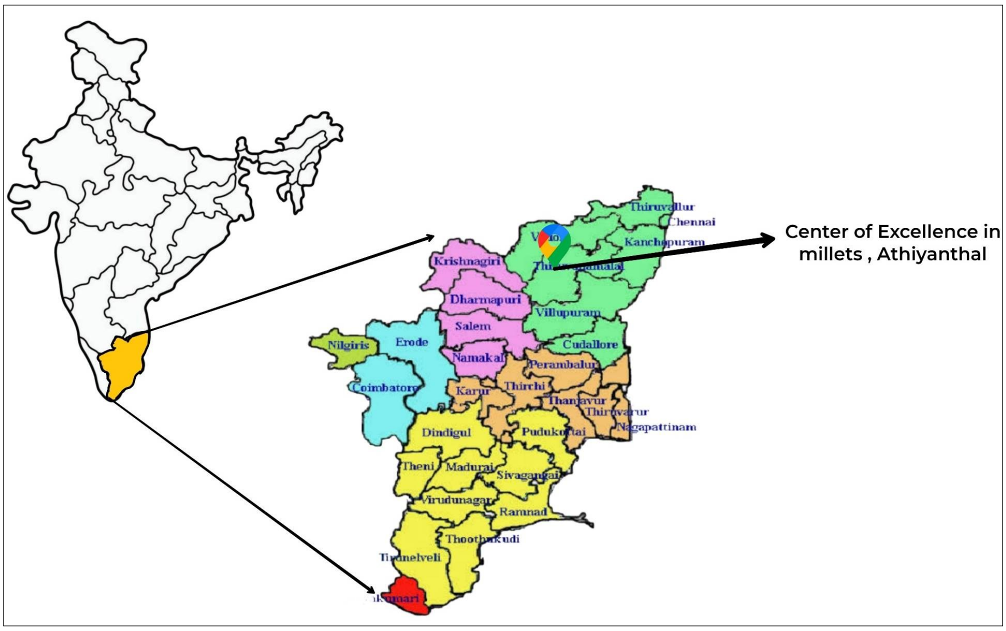

Fig. 2. Location of field experiment site.

population. Gap filling involved replanting in areas where seeds failed to germinate, ensuring uniform crop density, while thinning involved removing weaker or excess plants to reduce competition for resources such as light, nutrients and water. These practices promoted overall plant health and maximized yield potential by maintaining a balanced and healthy crop stand.

From the net plot area, five plants were randomly selected from each plot and tagged for growth traits measurements. Plant height was calculated by measuring the distance from ground level to the tip of the main shoot at 30 DAS, 60 DAS and at maturity stage and was expressed in cm. Additionally, the total number of leaves per plant was recorded, along with the length and width of the third leaf from the top of the tagged plants, to calculate the leaf area index using the formula recommended by 39.

Chlorophyll content was measured using a SPAD meter for non-destructive measurement on the fully expanded third leaf from the top. Five measurements were taken per plot and averaged to represent the chlorophyll content for each plot. These measurements were recorded on clear, sunny days between 09:00 h and 11:30 h. Data collection was conducted at various growth stages, including seedling, vegetative, flowering,and maturity, with the the average values across these stages presented.

The plants were harvested at ground level upon reaching physiological maturity. Productive tillers from the tagged plants were individually collected to determine the grain yield, which was expressed in grams per plant after manual threshing, cleaning and drying to a moisture content of 12-14%. The remaining plant samples were dried at 65±5° C for 48 hr to record dry matter production, expressed in kg/ha. Additionally, 1000 grains were randomly selected from five plants, weighed and expressed in grams (g).

The crop growth rate (CGR) was estimated at 30 DAS, 60 DAS and at maturity stage and was expressed in g/m^2/day (40). The economic viability of the intercropping system was evaluated using indicators such as gross returns (₹/ha), net returns (₹/ha) and the B:C ratio. Market prices of the produce were considered based on the average prevailing prices during the respective years of the study. The statistical significance of yield parameters and overall yield was assessed using ANOVA at the 5% probability level of significance (41).

Foxtail millet equivalent yield (FMEY)

The conversion of yields from different intercrops into a single unit was performed on a market price basis, enabling the identification of the most economically viable cropping combinations.

$$\text{FMEY (kg/ha)} = \frac{\text{Yield of intercrop} \times \text{Price of intercrop}}{\text{Price of foxtail millet}} + \text{Yield of foxtail millet}$$

Harvest index (HI)

HI was calculated as the ratio of economic yield (grain weight) to total biological yield (total plant biomass), expressed as a percentage:

This metric is used to assess the efficiency of a plant in allocating resources to grain production relative to total plant growth. The harvest index was measured at full maturity for each treatment to evaluate the productivity and resource-use efficiency of the crops under different experimental conditions.

$$\text{HI} = (\text{Grain Yield} / \text{Total Biomass Yield}) \times 100$$

Results and Discussion

Sole foxtail millet

The sole foxtail millet treatment exhibited promising performance, with a plant height at harvest reaching 105.6 cm (Table 1.). The number of productive tillers per plant was recorded at 5.3, While the panicle length measured 15.6 cm. These attributes contributed to a substantial grain yield of 2050 kg/ha and a significant straw yield of 3000 kg/ha. The harvest index was calculated at 68.3%, indicating efficient resource allocation. The foxtail millet equivalent yield mirrored the grain yield at 2050 kg/ha.

Additionally, the economic viability of sole foxtail millet cultivated was evident, with the benefit-to-cost (B:C) ratio recorded at 2.39, underscoring the favorable economic returns associated with this cropping system. Similar findings have been reported by (42, 43), indicating that foxtail millet cultivated as a sole crop outperformed intercropped treatments in terms of yield.

Table 1. Growth parameters of main crop foxtail millet

	Treatments	Plant height at harvest (cm)	No. of productive tillers/plant	Leaf area index	CGR (mg/g/m^2)	SPAD value	Length of panicle (cm)
T_1	Sole foxtail millet	105.6	5.3	2.68	35.4	26.1	15.6
T_2	Foxtail millet + Groundnut in a 4:1 ratio	100.3	4.2	2.67	34.8	26.9	14.0
T_3	Foxtail millet + Groundnut in a 6:1 ratio	103.4	4.8	2.59	34.3	25.3	14.4
T_4	Foxtail millet + Sesame in a 4:1 ratio	108.2	5.0	2.64	33.5	26.8	14.2
T_5	Foxtail millet + Sesame in a 6:1 ratio	106.5	5.4	2.48	34.1	26.4	13.8
T_6	Foxtail millet + Niger in a 4:1 ratio	105.2	5.0	2.52	33.9	25.8	14.6
T_7	Foxtail millet + Niger in a 6:1 ratio	99.2	5.4	2.44	33.2	25.4	14.2
	S.Ed	0.13	3.29	0.009	0.076	0.05	0.43
	CD (p=0.05)	0.29	7.01	0.023	0.166	0.11	1.37

Foxtail millet + Groundnut intercropping system

The success of an intercropping system is decided by the selection of component crops and the planting system employed (Fig.4.). In the case of foxtail millet and groundnut, competition for essential resources such as water, nutrients and sunlight may rise, potentially leading to reduced yields for one or both crops. Careful management is required to balance the resource use. Additionally, differences in optimal harvest timings between foxtail millet and groundnut pose a challenge, as delaying the harvest of one crop may negatively impact the other. Research has indicated that intercropping efficiency varies significantly depending on the planting system and the component crops involved (44).

A comparison between sole foxtail millet cultivation and its intercropping with groundnut in 4:1 and 6:1 ratios unveils nuanced agricultural dynamics (Table 1, 2.). In the 4:1 ratio, intercropped foxtail millet displayed a plant height of 100.3 cm at harvest, with 4.2 productive tillers/ plant, a panicle length of 14.0 cm and a grain yield of 1638 kg/ha. The 6:1 ratio exhibited improved growth parameters, including a higher plant height (103.4 cm), a higher number of tillers /plant (4.8) and a longer panicle (14.4 cm), resulting in a superior grain equivalent yield of 1865 kg/ha. This improvement is primarily attributed to the increased yield and elevated market price of groundnut (45, 46).

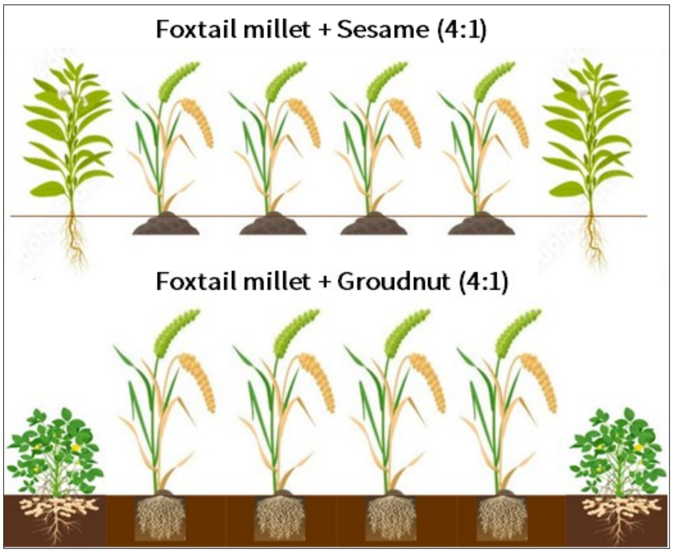

Fig. 4. Influence of foxtail millet + sesame (4:1) and foxtail millet + groundnut (4:1) intercrops.

Notably, the 6:1 ratio demonstrated a significantly higher harvest index (75.8%), signifying more efficient resource allocation towards grain production. Both intercropping ratios displayed economic viability, with the 6:1 ratio showing g slightly better relative production efficiency (6.3%), economic efficiency (10.8%) and a comparable benefit -to-cost ratio (2.54). These finding suggests that the 6:1 intercropping system holds potential for optimizing both yield and economic returns. Furthermore, it was documented that intercropping with pulses at an 8:2 ratio led to an enhancement in yield attributes of little millet, including the number of tillers per plant and 1000-grain weight (47). These observed improvements were comparable to those achieved in sole little millet crop.

Foxtail millet + Sesame intercropping system

Intercropping millets with sesame, due to its their distinctive growth habits, optimizes resource utilization and enhance overall productivity. This combination results in diversified yields, with millets producing nutrient-rich grains while sesame contributes oil-rich seeds. Additionally, the combined canopy structure of both crops aids in effective weed suppression by shading the soil, thereby reducing weed growth more effectively than monoculture systems (Fig.4.).

The comparison between sole foxtail millet cultivation and its intercropping with sesame at 4:1 and 6:1 ratios reveals distinct agricultural outcomes (Table 2). The statistical significance of the differences among treatments was assessed using ANOVA at a 5% probability level, with significant differences ($p \leq 0.05$) indicated by the CD values. In the 4:1 ratio, intercropping resulted in a plant height of 108.2 cm at harvest, with 5.0 productive tillers/plant and a panicle length of 14.2 cm. The grain yield was 1723 kg/ha, while the straw yield reached 2967 kg/ha. The harvest index was 58.1% and the foxtail millet equivalent yield stood at 2266 kg/ha, which can be attributed to an elevated market price.

In the 6:1 ratio, plant height was recorded at 106.5 cm, with 5.4 productive tillers/plant and a panicle length of 13.8 cm. Notably, the grain yield increased to 1840 kg/ ha, with a straw yield of 2306 kg/ha. The harvest index substantially improved to 80.9% and the foxtail millet equivalent yield reached 2226 kg/ha.

Table 2. Yield parameters of main crop foxtail millet

	Treatments	Grain yield (kg/ha)	Inter crop yield	Straw yield (kg/ha)	Harvest index (%)	Foxtail millet equivalent yield	B: C ratio
T_1	Sole foxtail millet	2050	-	3000	68.3	2050	2.39
T_2	Foxtail millet + Groundnut in a 4:1 ratio	1638	165	2744	59.7	2195	2.56
T_3	Foxtail millet + Groundnut in a 6:1 ratio	1865	110	2460	75.8	2179	2.54
T_4	Foxtail millet + Sesame in a 4:1 ratio	1723	190	2967	58.1	2266	2.64
T_5	Foxtail millet + Sesame in a 6:1 ratio	1840	135	2306	80.9	2226	2.60
T_6	Foxtail millet + Niger in a 4:1 ratio	1670	210	2635	63.4	2090	2.40
T_7	Foxtail millet + Niger in a 6:1 ratio	1825	106	2215	82.4	2076	2.35
	S.Ed	0.59	-	18.68	37.84	-	-
	CD (p=0.05)	1.58	-	36.9	76.88	-	-

Economic metrics demonstrated that the 4:1 ratio had higher relative production efficiency (10.5%), relative economic efficiency (18.1%) and a benefit-to-cost ratio of 2.64. The 6:1 ratio also exhibited competitive values, with relative production efficiency at 8.6%, relative economic efficiency at 16.8% and a benefit-to-cost ratio of 2.60. These results emphasize the potential for optimizing intercropping ratios to enhance not only crop growth and yield but also the economic sustainability of farming systems.

The 4:1 ratio, with its higher economic efficiency, presents an opportunity to improve farm profitability by optimizing input costs and maximizing yields. This is particularly crucial in regions where economic pressures and resource constraints pose significant challenges. The adoption of intercropping systems that promote both environmental sustainability and financial stability could encourage broader adoption of these practices across similar agro-ecosystems (48, 49).

Foxtail millet + Niger intercropping system

Niger is a valuable crop with multifaceted benefits. Primarily cultivated for its oil-rich seeds, it provides an edible oil with a favorable fatty acid composition, making it suitable for culinary use (Fig.5). Additionally, niger oil is utilized in various industrial processes, including paint and soap production (50). Economically, niger cultivation offers income opportunities for farmers, contributing to rural livelihoods. Overall, niger is a resilient and versatile crop with significant nutritional, economic and environmental implications.

The comparison of sole foxtail millet cultivation with its intercropping alongside niger in 4:1 and 6:1 ratios reveals significant variations in agricultural outcomes (Table 1.). In the 4:1 intercropping ratio, the plant exhibited a height of 105.2 cm, with 5.0 productive tillers per plant and a panicle length of 14.6 cm. The grain yield was recorded 1670 kg/ha, with the straw yield reached 2635 kg/ha. The harvest index was calculated at 63.4% and the foxtail millet equivalent yield stood at 2090 kg/ha.

In contrast, the 6:1 ratio exhibited a slightly shorter plant height of 99.2 cm, with 5.4 productive tillers per plant and a panicle length of 14.2 cm. However, the grain yield increased to 1825 kg/ha, whereas the straw yield decreased to 2215 kg/ha (51). Notably, the harvest index showed a substantial improvement, reaching 82.4%, while the foxtail millet equivalent yield was 2076 kg/ha.

Economic metrics revealed that the 4:1 ratio displayed higher relative production efficiency (2.0%), relative economic efficiency (3.4%) and a benefit-to-cost (B: C) ratio of 2.40. Conversely, the 6:1 ratio demonstrated slightly lower but competitive values, with relative production efficiency at 1.3%, relative economic efficiency at 2.2% and a B:C ratio of 2.35. The reduced benefit-to-cost ratio in the 6:1 ratio can be attributed to increased cultivation expenses and declining market prices. These outcomes are consistent with the research findings (52).

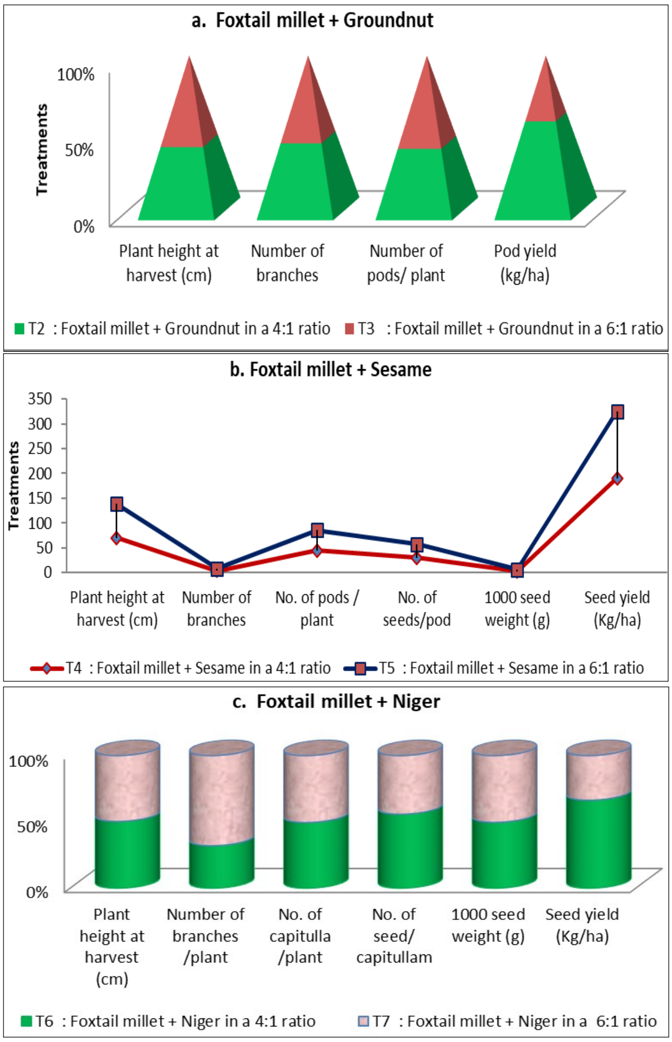

Fig. 5. Growth and yield parameters of foxtail millet + oilseeds intercropping system.

Intercrop yield

The integration of multiple crops in an intercropping system, such as foxtail millet with groundnut, sesame and niger in varying ratios, facilitates a detailed analysis of their combined agronomic performance (Table 2.).

In the foxtail millet + groundnut intercrop, the 4:1 ratio resulted in groundnut plants with a height of 52.2 cm, with 5.6 branches per plant and an average of 7.8 pods per plant, leading to a pod yield of 165 kg/ha. On the other hand, in the 6:1 ratio, groundnut plants grew taller (65.3 cm) and exhibited an increased number of branches (6.4) and pods per plant (10.2). However, despite these improvements in individual plant characteristics, the pod yield was slightly lower (110 kg/ha).

In the foxtail millet + sesame intercrop, the 4:1 ratio produced sesame plants reaching a height of 70.1 cm, with 4.0 branches per plants and an impressive 44.6 pods per plant (Fig.5). This configuration yielded 190 kg/ha of sesame. In contrast, the 6:1 ratio resulted in slightly shorter sesame plants (68.3 cm) with fewer branches (3.8) and pods per plant (41.2), leading to a reduced seed yield of 135 kg/ha. This contrast underscores the complex relationship between plant characteristics and yield outcome in an intercropping system.

Regarding the foxtail millet + niger intercrop , the 4:1 ratio showcased niger plants towering at 82.4 cm, with 8.6

branches per plant and an abundant 192 capitula per plant. This configuration resulted in a seed yield of 210 kg/ha. In the 6:1 ratio, although niger plants were slightly shorter (81.0 cm) and exhibited a higher number of branches (18.2). However, the number of capitula per plant was reduced to 184, leading to a diminished seed yield of 106 kg/ha. This illustrates the delicate balance among plant height, branching patterns and reproductive structures, all of which influence the overall productivity of the intercropping system.

Effect of intercropping on physiological parameters

The table compares various intercropping treatments of foxtail millet with groundnut, sesame and niger, in terms of leaf area index (LAI), crop growth rate (CGR) and SPAD values (Table 1). Sole foxtail millet (T_1) has the highest LAI (2.68) and CGR (35.4 mg/g/m^2). However, the foxtail millet + groundnut intercropping system in a 4:1 ratio (T_2) demonstrates a comparable LAI (2.67) and a nearly comparable CGR (34.8 mg/g/m^2), while also recording the highest SPAD value (26.9), indicating optimal chlorophyll content.

Among the intercropped treatments, the foxtail millet + sesame combination in a 4:1 ratio (T_4) maintained a high LAI (2.64) and a favorable SPAD value (26.8), though its CGR was slightly lower (33.5 mg/g/m^2). In contrast, the foxtail millet + niger intercropping treatments (T_6 and T_7) show moderate LAI and CGR values. The T6 (4:1 ratio) showed a relatively higher LAI (2.52) and CGR (33.9 mg/g/m^2) compared to T7 (6:1 ratio), which recorded the lowest values among the intercropped treatments.

These results suggest that intercropping foxtail millet with groundnut in a 4:1 ratio is the most effective strategy for maintaining a high leaf area and growth rate while optimizing chlorophyll content. Similar observations have been reported in previous studies (53, 54).

Effect of intercropping in competitive functions

The table evaluates the performance of various intercropping treatments of foxtail millet paired with groundnut, sesame and niger in different ratios (Table 3). The foxtail millet + sesame intercrop in a 4:1 ratio exhibited the highest land equivalent ratio (LER) (1.16), relative production efficiency (10.5%) and relative economic efficiency (18.1%), indicating superior land use and economic returns. Conversely, the foxtail millet + niger intercrop in a 6:1 ratio shows the lowest efficiency, with an LER of 1.06, a production efficiency of 1.3% and an economic efficiency of 2.2% (Fig.6).

In terms of crop dominance, foxtail millet generally exhibited greater dominance, particularly when intercropped with groundnut (6:1 ratio), where it had a high competitive ratio (6.89). Meanwhile, sesame and niger were less competitive against millet, as reflected in their lower competitive ratios and negative or minimal aggressivity values. These similar findings align with previous research(54).

Economics

The Benefit-Cost (B: C) ratio, a key financial metric gauging the economic efficiency of intercropping systems, varied across different combinations of foxtail millet with groundnut, sesame and niger in 4:1 and 6:1 ratios (Table 2.). Notably, the foxtail millet + groundnut intercrop in a 4:1 ratio demonstrates the highest B: C ratio at 3.14, indicating strong economic returns and efficient resource utilization in this specific intercropping arrangement.

Following closely, the foxtail millet + sesame (4:1) and foxtail millet + niger (4:1) intercropping systems yielded B: C ratios of 2.91 and 2.48, respectively, further highlighting their economic benefits. Conversely, the foxtail millet + groundnut (6:1) and foxtail millet + niger (6:1) intercropping treatments exhibited lower B: C ratios of 2.61 and 1.96, respectively.

Several studies support the beneficial effects of different intercropping systems, like research revealed that intercropping groundnut and little millet in a 6:1 row proportion significantly improved resource use efficiency (LER 1.13) and yielded a higher benefit-cost ratio (2.16) compared to sole cropping of groundnut or little millet (55). Similarly, the result highlighted the benefits of intercropping little millet and pigeon pea at 6:1 or 6:2 ratios, emphasizing the potential yield and economic benefits of such system (56).

Additional research has demonstrated that intercropping pigeon pea with proso millet in a 1:2 ratio resulted in higher net returns and a superior benefit-cost ratio compared to monocropping. Similarly, the result found that intercropping proso millet with mung bean led to a substantial yield increase of 6.8% to 37.3% over solo proso

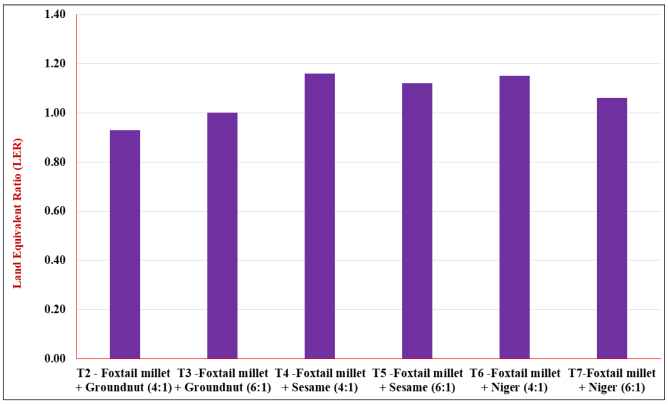

Fig. 6. Land equivalent ratio in cropping system.

Table 3. Effect of intercropping system on competitive functions

Treatments	Land equivalent ratio	Relative production efficiency (%)	Relative Economics efficiency (%)	Aggresivity	Competitive ratio
T_2 - Foxtail millet + Groundnut (4:1)	0.93	7.4	12.2	0.13	2.02
T_3 -Foxtail millet + Groundnut (6:1)	1.00	6.3	10.8	0.26	6.89
T_4 -Foxtail millet + Sesame (4:1)	1.16	10.5	18.1	-0.11	0.66
T_5 -Foxtail millet + Sesame (6:1)	1.12	8.6	16.8	0.11	1.99
T_6 -Foxtail millet + Niger (4:1)	1.15	2.0	3.4	-0.19	0.41
T_7-Foxtail millet + Niger (6:1)	1.06	1.3	2.2	-0.06	0.67

millet cropping (54). Notably, the proso millet + mung bean intercropping system in a 2:4 ratio improved resource use efficiency, enhanced photosynthate production and optimized sink conversion, further supporting the viability of intercropping as a sustainable agricultural practice.

Conclusion

This study focuses on identifying profitable and economically viable intercropping strategies involving foxtail millet and oil seeds while assessing optimal row patterns to foster a complementary interaction between these component crops. Several notable findings have emerged from the research.

Initially, it was observed that sole cultivation of foxtail millet, also known as Tenai, yielded higher grain production compared to intercropping systems. Among the various intercropping systems examined, sesame exhibited notable performance, outperforming both groundnut and niger. Interestingly, groundnut growth was impeded after 30 days due to the vigorous growth of foxtail millet, affecting its overall development.

In terms of yield, foxtail millet as a sole crop achieved 2050 kg/ha, while the combination of foxtail millet with sesame (4:1) intercrop recorded the highest equivalent yield of 2226 kg/ha, surpassing all other intercropping approaches except for foxtail millet + groundnut in a 4:1. Moreover, intercropping foxtail millet with oil seeds in a 4:1 ratio resulted in favorable benefit-cost (B:C) ratios ranging from 2.40 to 2.64. The highest profitability was observed in intercropping foxtail millet with sesame, followed by groundnut in a 4:1 ratio. Conversely, intercropping at a 6:1 ratio proved less lucrative due to lower oil seed yields, which subsequently reduced gross income.

The study also highlights a declining trend in foxtail millet cultivation, as many farmers are reluctant to grow it as a sole crop due to its lower yield and economic returns, leading to its gradual disappearance from cropping systems and food consumption. However, by demonstrating the compatibility and economic advantages of intercropping foxtail millet with main crops, this study presents a sustainable approach to preserving traditional crop cultivation without compromising yield and income. To increase awareness and boost foxtail millet production, it is essential to conduct demonstration programs through various schemes, implement development procurement policies similar to those for rice and wheat, promote the adoption of diverse cropping systems and facilitate the supply of foxtail millet through the Public Distribution System (PDS).

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Authors' contributions

All the authors equally contributed for this study.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests.

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