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RESEARCH ARTICLE

Optimizing row patterns to enhance productivity, quality and profitability in soybean-maize intercropping systems

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Abstract

The optimal row patterns in maize-soybean intercropping enhance resource use efficiency, land productivity and profitability, promoting sustainability in resource-limited regions. The experiment was conducted at the CAU Research Farm in Imphal, Manipur, during the kharif season of 2022-23. Seven treatments were tested, including sole soybean, sole maize and five maize-soybean intercropping combinations (2:2, 3:1, 3:2, 4:1, 4:2), with four replications each. The results showed that sole crops performed better than intercropped treatments in most growth and yield parameters. Among intercropping treatments, 3S:1M (three rows of soybean to one row of maize) configuration achieved the highest seed yield, with 775 kg ha^{-1} for soybean and 4006 kg ha^{-1} for maize. The correlation analysis indicated strong associations between soybean grain yield with dry matter accumulation (r = 0.948) and the number of pods per plant (r = 0.944). In contrast, maize yield was linked to the crop growth rate (r = 0.957) and the number of cobs per plant (r = 0.924). Principal component analysis (PCA) identified biomass and pod production as the primary contributors to yield variation in soybean and dry matter accumulation and crop growth rate for maize. One row of maize intercropped between three rows of soybean showed the highest land equivalent ratio (1.44), indicating a yield advantage over sole cropping, alongside the highest economic performance with a net return of ₹ 103123 and a benefit-cost ratio of 3.21. Maize exhibited dominance over soybean in intercropping, with an aggressivity index of 0.55. These findings suggest that one row of maize intercropped between three rows of soybean intercropping patterns optimizes productivity and profitability, providing a sustainable solution for smallholder farmers.

Keywords: correlation matrix; crude protein; intercropping; land equivalent ratio; principal component analysis

Introduction

Indias' share of global pulse production was 25.8 % and ranked first in production. It is the largest producer and consumer of pulses, cultivating pulses over 28.99 million hectares with a productivity rate of 0.84 t ha^{-1} (1). Soybean (*Glycine max*) and maize (*Zea mays*) play crucial roles worldwide in agriculture and food systems, each providing distinctive nutritional and economic benefits. Soybean, celebrated as the leading legume crop globally, belongs to the family Fabaceae. It contributes approximately 25 % of the worlds' edible oil production and is a primary protein source for livestock feed (2). In addition to its nutritional value, soybeans' high protein content (33-45 %) and unique amino acid profile, rich in lysine, make it one of the best vegetable protein sources for humans and animals. Its nutrient-rich profile also includes carbohydrates (22-33 %) and fat (16-22 %), supporting a wide range of applications in the food, pharmaceutical and industrial sectors (3 and 4).

The global soybean production in 2022-23 was approximately 348.86 million metric tons. Brazil and the United States are the largest producers, accounting for 35 % and 33 % of the total production, respectively (5). India ranks fourth globally in land area and fifth in production, with an annual output of 14985 tonnes cultivated across 13084 hectares in 2022-2023 (6). Furthermore, soybeans have a significant role in sustainable agriculture, enhancing soil fertility by fixing atmospheric nitrogen at 65-115 kg ha^{-1}, a critical process for nutrient recycling (7).

Maize, often called the "Queen of Cereals," belongs to the Poaceae family. Recognized for its high yield potential and versatility, maize originates from Mexico and Central America and has adapted to various agro-climatic conditions, making it a staple crop globally. In 2022 global maize production reached 1163 million metric tonnes across 205.87 million hectares. The USA was the leading producer of maize (35 %) and it was followed by China (24 %) (5). India ranked fourth in acreage and sixth in production, contributing 3.96 % and 2.13 %, respectively (8, 5). In 2022-23, the total maize area covered 9.2 million hectares, yielding a total production of 34.6 million tonnes, with an average productivity of 3.19 tonnes per hectare. Maize is widely cultivated for its nutritional profile, containing about 72 % starch, 10 % protein and essential micronutrients, making it a dietary staple in many developing countries (9). The cereal also plays a significant role in food security, industrial applications and as a feedstock for animal husbandry, further establishing its value across global agriculture. In North Eastern states, maize is primarily cultivated under rainfed conditions, contributing to food security (10).

Intercropping, or polyculture, involves growing two or more crops on the same plot and is a traditional agricultural practice known for optimizing resource use and enhancing productivity. The benefits of intercropping are well-established: better light utilization, more efficient nutrient uptake and increased crop diversity resulting in improved resilience against environmental stressors and pest pressures (11). Cereal-legume combinations like maize and soybean have gained popularity among various intercropping systems due to their complementary characteristics. Soybeans' nitrogen-fixing ability enriches the soil, benefiting maize with a high nitrogen demand. Conversely, maizes' taller stature optimizes light interception for both crops when grown in a mixed pattern (12). Research findings revealed that maize-soybean intercropping can naturally suppress weeds by increasing canopy coverage, reducing reliance on (13, 14). However, using inorganic nitrogen fertilizers in maize and soybean cultivation contributes to nitrogen pollution through leaching, water contamination and nitrous oxide emissions. In maize, excessive fertilizer application often leads to inefficient nitrogen uptake, while in soybean, synthetic fertilizers can inhibit its natural nitrogen fixation, leaving excess nitrogen in the system. To address these challenges, nitrogen application in this experiment was managed through maize-soybean intercropping. The soybean: maize intercropping system improved nitrogen use efficiency, minimized nitrogen losses and mitigated environmental pollution, highlighting the sustainability advantages of maize-soybean intercropping systems. Optimizing row patterns is crucial to maximizing the potential of a maize-soybean intercropping system. Row patterns influence plant spacing, light distribution and root zone overlap, all impacting competition for nutrients, moisture and sunlight. Studies have indicated that strategic row configurations can improve crop yield, quality and economic returns by enabling each crop to fully exploit its growth resources while minimizing competition (15). For example, planting two rows of soybean between paired rows of maize has demonstrated more potential for resource use efficiency and yield than traditional single-row systems (16).

Therefore, this study investigates the impact of different row patterns on the productivity, competitive dynamics, quality and profitability of a maize-soybean intercropping system with the objectives (i) evaluate the growth and yield characteristics of maize and soybean in both sole and intercropped systems, (ii) assess intercropping advantages over monoculture through competition indices and light use efficiency and (iii) conduct an economic analysis to determine the most viable cropping system for resource-limited smallholder farmers.

Materials and Methods

Experimental site

The experiment was conducted at the CAU Research Farm Andro, Imphal, Manipur, during the 2022 kharif season. The experimental site, situated at 24°765' N latitude and 94°053' E longitude, is 795 m above sea level. Geographically, the site falls within the Eastern Himalayan Region (II) and the Subtropical Agroclimatic Zone (NEH-4). The Imphal Valley receives significant rainfall from June to September, averaging about 1212 mm annually. Meteorological data from the ICAR Research Complex for the NEH Region, Manipur Centre, Lamphelpat, Imphal, for the experimental period are illustrated in Fig. 1. During this period, the mean maximum and minimum temperatures were 30.1 °C and 21.95 °C, respectively. The highest rainfall occurred in July (148.4 mm), while the lowest was in August (94.8 mm). The mean maximum and minimum relative humidity were 86.10 % and 62.92 %, respectively. Composite samples were collected at the experimental site for physical and chemical analysis. The soil has a sandy clay texture, with an acidic pH (5.27) and medium levels of organic carbon (0.68 %), available nitrogen (285 kg ha^{-1}), phosphorus (22.7 kg ha^{-1}) and potassium (152.43 kg ha^{-1}).

Treatments and experimental design

The study was carried out using a Randomized block design (RBD) comprising seven treatments: sole soybean (T_1), sole maize (T_2), soybean + maize (2:2) (T_3), soybean + maize (3:1) (T_4), soybean + maize (3:2) (T_5), soybean + maize (4:1) (T_6) and soybean + maize (4:2) (T_7), replicated four times. The maize cultivar HQPM-5 and the soybean cultivar MACS 1460 were sown in July 2022 using the replacement method for intercropping, with spacings of 45 cm × 10 cm and 60cm × 20cm for soybean and maize, respectively. Essential nutrients (nitrogen, phosphorous and potassium) were supplied using urea, single super phosphate (SSP) and muriate of potash (MOP), respectively. At sowing, full doses of phosphorus, potassium and 50 % of nitrogen were applied as basal fertilizers, following recommended doses for soybean (20:40:40 kg ha^{-1}) and maize (120:60:80 kg ha^{-1}). The remaining 50 % of nitrogen fertilizer was top-dressed at the knee-height stage. Standard agronomic practices were followed throughout the crop-growing period and harvesting occurred at maturity. Before sowing, seed treatment with captan @ 2 g kg^{-1} seed was carried out.

Growth and yield parameters

Five randomly selected maize and soybean plants per plot were measured for plant height and dry matter accumulation at 30-day intervals. However, yield attributes were calculated by selecting ten plants randomly from each plot at harvest and yield was calculated after the harvest of the crop. The recorded values were averaged and expressed in appropriate units.

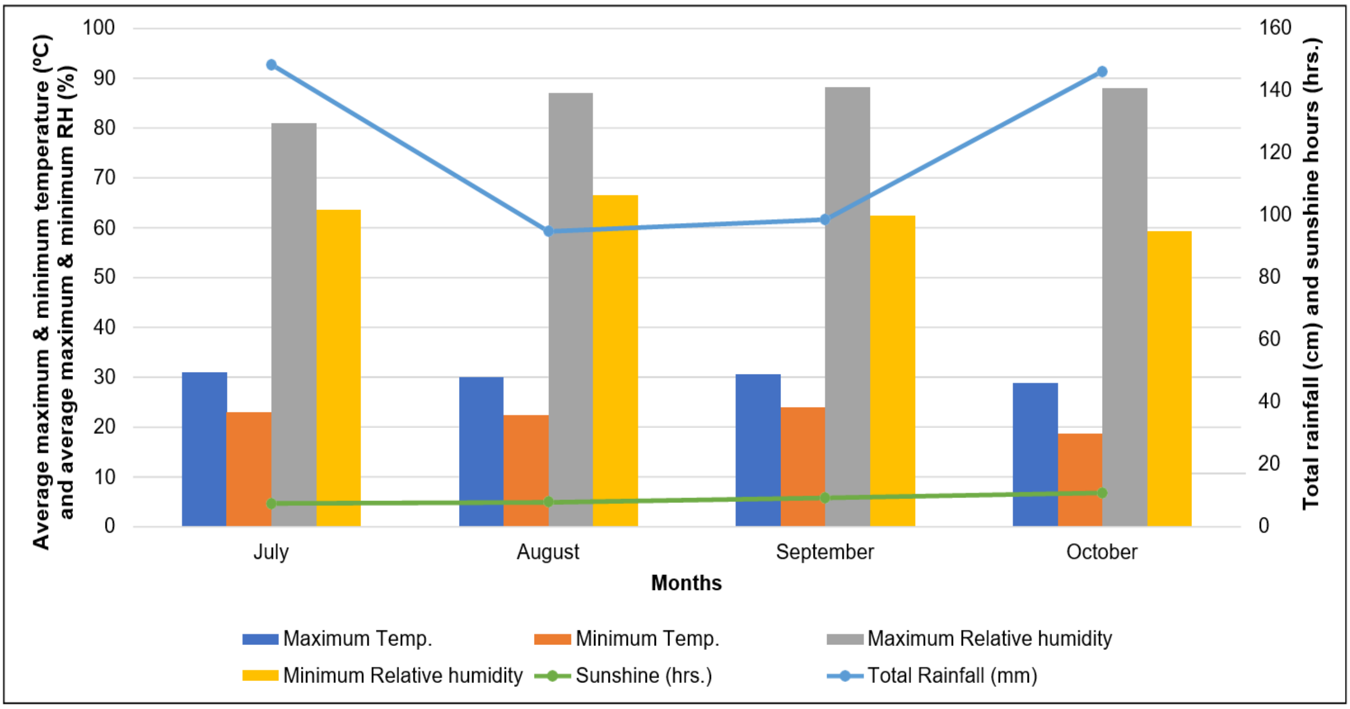


Fig. 1. Meteorological data indicating monthly rainfall, maximum and minimum temperature, maximum and minimum relative humidity and bright sunshine hours during crop growth period (July- October, 2022).

The harvest index was calculated using the economic yield/biological yield formula (17).

Competitive indices

Land equivalent ratio (LER)

LER was calculated by the prescribed formula provided in eqn. 1. (18)

$$\text{LER} = \frac{\text{Yield of the crop in mixture}}{\text{Yield of the main crop in sole}} + \frac{\text{Yield of the intercrop in mixture}}{\text{Yield of the intercrop in sole}} \qquad \text{(Eqn. 1)}$$

Aggressivity

Aggressivity was calculated by the given formula, provided in eq. 2. (19)

$$\text{Aggressivity} = \frac{\text{Yield of the main crop in sole}}{\text{Yield of the main crop in mixture x sown proportions of main crop}} + \frac{\text{Yield of the intercrop in sole}}{\text{Yield of the intercrop in mixture x Sown proportions of intercrop}} \qquad \text{(Eqn. 2)}$$

Relative crowding coefficient (RCC)

Relative Crowding Coefficient was calculated using the formula, provided in eq. 3 and 4, offering an assessment of how plant density influences the overall productivity of crops (20). Coefficients exceeding unity indicate unexpected yield increases, with the dominant crop identified by the higher coefficient value.

$$K_{ab} = \frac{\text{Yield of the main crop in mixture}}{\text{Yield of the main crop in sole - Yield of main crop in mixture}} \times \frac{\text{Sown proportion of Intercrop in mixture}}{\text{Sown proportion of Main crop in mixture}} \qquad \text{(Eqn. 3.)}$$

$$K_{ba} = \frac{\text{Yield of the inter crop in mixture}}{\text{Yield of the inter crop in sole - Yield of main inter in mixture}} \times \frac{\text{Sown proportion of main crop in mixture}}{\text{Sown proportion of inter crop in mixture}} \qquad \text{(Eqn. 4.)}$$

Where,

Kab = Co-efficient of species "a" in the presence of species "b"

Kba= Co-efficient of species "b" in the presence of species "a

The Monetary advantage index (MAI)

The monetary advantage index was calculated by the formula as outlined in Equation . 5. (21)

$$\text{MAI (Rs ha}^{-1}\text{)} = \frac{\text{LER -1}}{\text{LER}} \times \text{value of combined intercrop yield} \qquad \text{(Eqn. 5.)}$$

Soybean equivalent yield (SEY)

Soybean equivalent yield was calculated using the formula as described in equation 6 (22).

$$\text{SEY (Rs ha}^{-1}\text{)} = \text{Soybean yield (Kg ha}^{-1}\text{)} + \frac{\text{Maize yield (kg ha}^{-1}\text{) x Market price of maize (Rs ha}^{-1}\text{)}}{\text{Market price of Soybean (Rs ha}^{-1}\text{)}} \quad \text{(Eqn. 6)}$$

Economical parameters

Cost of cultivation: It was calculated by summing up the expenses incurred on various variable inputs used and expressed in Rs ha^{-1}.

Gross income (Rs ha^{-1}) = Grain yield (kg ha^{-1}) × Price (Rs) (Eqn. 7)

Net income (Rs ha^{-1}) = Gross income (Rs ha^{-1}) - Total cost of cultivation (Rs ha^{-1}) (Eqn. 8)

Benefit-cost (B:C) ratio = Gross Return / Cost of Cultivation (Eqn. 9)

Quality parameters

Crude protein content in soybean and maize

Seeds from each treatment were dried at 60 ± 5 °C and analyzed for crude protein analysis. Nitrogen content was determined using the modified Kjeldahls' method (23). The nitrogen percentage obtained from the analysis was multiplied by the factor 6.25 to calculate the protein percentage.

Oil content in soybean seeds

The soxhlet method and petroleum ether extraction were adopted to determine the oil content (23). The oil content in the seed was determined by the formula given in Equation 10 (24).

$$\text{Oil content (\%)} = \frac{W2 - W1}{X} \times 100 \quad \text{(Eqn. 10)}$$

Where,

W_1= Weight of the empty flask

W_2=Weight of the empty flask + weight of oil

X= Weight of the sample taken for extraction

Oil yield of soybean

The oil yield ha^{-1} for each treatment was computed by multiplying the seed yield (kg ha^{-1}) with the oil content of the respective treatment and expressing it as kg ha^{-1}.

Statistical analysis

Data obtained on various investigations were statistically analyzed in a randomized block design (RBD) using the Analysis of Variance (25) technique and different multivariate analyses done using R studio software, version 4.2.2. The data were statistically analyzed to get the critical difference values at a 5 % significance level and were presented in tables where necessary.

Results

Effect of row pattern on growth attributes of soybean

Plant height was significantly influenced at all observation dates except at 30 DAS (Table 1). This might be because maize plants had not yet developed enough to create heavy shading at early growth stages, resulting in no significant difference between sole and intercropped soybean treatments (26). As the plants matured, soybean height peaked at 60 DAS before slightly declining by harvest (Table 1). This pattern aligns with soybeans' growth stages, where vegetative growth culminates around 60 DAS, transitioning into reproductive phases leading to maturity. The slight reduction in plant height observed at harvest compared to 60 DAS can be attributed to the natural senescence processes associated with crop maturation. As soybean plants transition from full seed stage (R6) to maturity (R7-R8), resources are reallocated from vegetative structures to seed development, decreasing turgor pressure and potential slight reductions in measured plant height. Taller plants were observed in T_1 (58, 75.50 and 67 cm), which was statistically at par with T_4 (55.50, 70 and 61.75 cm) at all observation points except 30 DAS. The reduction in plant height under intercropping systems was likely due to increasing shade from taller maize plants as growth progressed. This shading effect limited the amount of light available to soybean, reducing its growth compared to sole soybean cultivation (27).

Dry matter accumulation showed no significant variation among treatments at 30 DAS. However, as the crop progressed, a steady increase in dry matter was observed, reaching its peak at harvest. At 45 DAS, a higher dry matter accumulation (9.57 g) was recorded in T_4, which was statistically at par with T_1 (9.16 g) and T_6 (8.78 g). By 60 DAS, T_1 exhibited a higher dry matter accumulation (16.52 g), closely followed by T_4 (14.87 g). At harvest, T_1 continued to have the highest dry matter accumulation (17.29 g), while other treatments recorded lower values (Table 1). Increasing the row spacing between soybean and maize improved dry matter accumulation in soybean plants. Wider spacing reduced shading, allowing better light penetration and higher dry-weight production per plant (28). Similar observations have been reported in other studies (29, 30). Intercropping patterns did not significantly influence the crop growth rate (CGR) of soybean. Across different treatments, CGR ranged from 7.58 to 10.13 g m^{-2} day^{-1} during 30 DAS-45 DAS and 7.58 to 10.79 g m^{-2} day^{-1} during 45 DAS-60 DAS.

Effect of Row Patterns on yield attributes of soybean

The highest number of pods plant^{-1} (63.25) was recorded under T_1 (sole soybean). Among the intercropped treatments, T_6, T_4 and T_7 had higher pod numbers, with 54, 52.75 and 50.25 pods per plant, respectively (Table 2). The reduction in pod numbers under intercropping compared to sole soybean cultivation was likely due to interspecific competition and the suppressive effect of maize on soybean. This competition restricted dry matter production, limiting nutrient availability and assimilating necessary for pod formation and seed development (31, 32). Similar observations have been reported in previous studies (26, 29). No significant variation was found in the effect of row patterns on number of seed

Table 1. Effect of row patterns on growth attributes of soybean

Treatments	Plant height (cm)				Dry matter accumulation (g)				CGR (g m^{-2} day^{-1})	
	30 DAS	45 DAS	60 DAS	Harvest	30 DAS	45 DAS	60 DAS	Harvest	30-45 DAS	45-60 DAS
T_1 (Sole Soybean)	29.25	58.00^{a}	75.50^{a}	67.00^{a}	3.00	9.16^{ab}	16.52^{a}	17.29^{a}	9.03	10.79
T_3 (2S:2M)	24.00	47.00^{c}	62.50^{b}	54.50^{b}	2.41	7.57^{c}	12.99^{b}	13.03^{b}	7.58	7.95
T_4 (3S:1M)	25.00	55.50^{ab}	70.00^{ab}	61.75^{ab}	2.66	9.57^{a}	14.87^{ab}	15.06^{b}	10.13	7.77
T_5 (3S:2M)	26.50	51.00^{abc}	63.25^{b}	56.50^{b}	2.49	8.41^{abc}	13.88^{b}	14.36^{b}	8.67	8.03
T_6 (4S:1M)	26.50	52.75^{abc}	65.50^{b}	61.00^{ab}	2.85	8.78^{ab}	14.50^{b}	14.86^{b}	8.70	8.40
T_7 (4S:2M)	25.00	48.75^{bc}	64.25^{b}	54.75^{b}	2.26	8.27^{bc}	13.82^{b}	14.46^{b}	8.81	8.15
SE(m)±	1.38	2.28	2.51	2.44	0.166	0.36	0.63	0.70	0.659	0.998
CD (*p*=0.05)	NS	6.87	7.59	7.35	NS	1.09	1.90	2.13	NS	NS

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant; DAS: Days after sowing; CGR: Crop growth rate

Table 2. Effect of row patterns on yield attributes of soybean

Treatments	Yield attributes	
	No. pods plant^{-1}	No. of seeds pod^{-1}
T_1 (Sole soybean)	63.25^{a}	2.70
T_3 (2S:2M)	44.75^{cd}	2.45
T_4 (3S:1M)	52.75^{bc}	2.68
T_5 (3S:2M)	40.00^{d}	2.63
T_6 (4S:1M)	54.00^{b}	2.48
T_7 (4S:2M)	50.25^{bc}	2.60
SE(m)±	2.71	0.11
CD (*p*=0.05)	8.18	NS

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant

pod^{-1}.

Effect of row patterns on yield and harvest index of soybean

Soybean yield varied significantly across treatments. The highest seed yield (1155.50 kg ha^{-1}) was recorded under T_1, significantly higher than all intercropped treatments (Table 5). This can be attributed to the optimal plant population in the sole crop, while intercropping reduced soybean plant density by 75 %, leading to lower grain yield (33). The sole crop benefited from better access to essential resources such as nutrients, moisture, light and space, contributing to superior growth and yield. Among the intercropping treatments, T_6 recorded a higher seed yield (819.25 kg ha^{-1}), which was statistically at par with T_7 (790.50 kg ha^{-1}) and T_4 (775.00 kg ha^{-1}). The higher yield in these treatments was likely due to the increased soybean plant density in the 4:1 proportion, leading to more significant pod formation and higher dry matter accumulation per unit area. However, intercropping resulted in a 30 % reduction in seed yield compared to the sole crop. This decline was primarily due to variations in planting geometry and row proportions, affecting plant stand and resource availability. The shading effect of maize restricted light penetration, reducing photosynthesis and nutrient uptake for flower and pod development. This, in turn, led to increased flower and pod drop, ultimately resulting in lower yield (26, 34).

Sole soybean treatment (T_1) recorded a higher stover yield (1723.35 kg ha^{-1}), which was found to be statistically at par with T_6 (1711.75 kg ha^{-1}), T_7 (1691.25 kg ha^{-1}), T_4 (1688.75 kg ha^{-1}) and T_5 (1504.50 kg ha^{-1}) (Table 5). The increased stover yield in these treatments can be attributed to reduced interspecific competition for light and water during peak growth stages and a higher plant stand than maize. However, a higher harvest index (HI) was recorded in T_3 (43.73 %) and was on par with T_1 (43.55 %). These results indicate that sole soybean cropping and the 2S:2M intercropping system maintained a higher proportion of seed yield relative to total biomass. In contrast, other intercropping treatments resulted in a lower HI due to increased stover production.

Effect of row patterns on growth attributes of maize

The plant height of maize increased progressively with crop age, attaining its maximum at 90 DAS, followed by a slight reduction at harvest (Table 3). This pattern is consistent with the physiological growth stages of maize, wherein the crop attains its peak vegetative growth by around 90 DAS, which often coincides with the onset of physiological maturity. Among the treatments, the tallest plants were consistently recorded in T_2 treatment, with plant heights of 85.95, 183.15, 228.40 and 214.45 cm at 30, 60, 90 DAS and harvest, respectively. At 30 DAS, T_2 was statistically at par with T_5 (83.10 cm) and T_7 (80.40 cm). At 60 DAS, T_2 was at par with T_3 (179.77 cm), T_5 (170.67 cm) and T_7 (181.90 cm), while at 90 DAS and harvest, it was statistically similar to T_3

Table 3. Effect of row patterns on growth attributes of maize

Treatments	Plant height (cm)				Dry matter accumulation (g)				CGR (g m^{-2} day^{-1})	
	30 DAS	60 DAS	90 DAS	Harvest	30 DAS	60 DAS	90 DAS	Harvest	30-60 DAS	60-90 DAS
T-$_2$(Sole Maize)	85.95^a	183.15^a	228.40^a	214.45^a	15.35^a	43.80^a	154.02^a	164.77^a	7.59	29.39
T_3 (2S:2M)	78.35^{bcd}	179.77^{abc}	212.400^{ab}	201.30^a	12.60^b	36.90^{bc}	122.93^b	132.62^b	6.48	22.94
T_4 (3S:1M)	73.70^{cd}	168.30^{bc}	201.57^{bc}	185.05^b	12.51^b	34.83^c	118.37^b	127.27^b	5.95	22.28
T_5 (3S:2M)	83.10^{ab}	170.67^{abc}	203.85^{bc}	183.50^b	12.93^b	40.25^{abc}	123.81^b	128.99^b	7.28	22.28
T_6 (4S:1M)	72.42^d	165.77^c	188.90^c	175.27^b	12.44^b	33.67^c	114.34^b	124.97^b	5.66	21.51
T_7 (4S:2M)	80.40^{abc}	181.90^{ab}	226.77^a	202.60^a	13.20^b	42.73^{ab}	128.71^b	135.37^b	7.88	22.93
SE(m)±	2.13	4.38	6.25	4.38	0.41	2.10	6.52	3.91	0.58	1.97
CD (*p*=0.05)	6.44	13.21	18.85	13.20	1.26	6.34	19.68	11.8	NS	NS

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant; DAS: Days after sowing; CGR: Crop growth rate

(212.40 cm and 201.30 cm) and T_7 (226.77 cm and 202.60 cm), respectively.

The marginal reduction in plant height observed at harvest compared to 90 DAS can be attributed to the natural senescence processes associated with crop maturity. Maize plants reached physiological maturity around 90 DAS, after which active vegetative growth ceased. During the subsequent period leading to harvest maturity, the remobilization of assimilates from vegetative tissues (leaves and stem) to reproductive organs (grain) occurred, accompanied by moisture loss and tissue desiccation. This dry matter partitioning, along with the browning of leaves, drying of stalks and tassel degradation, may lead to a slight decrease in plant height measurements due to the collapse or shrinkage of upper internodes and loss of turgidity. Furthermore, since harvest was timed to coincide with field maturity, characterized by drying and senescence symptoms, plant structures were more fragile and less erect than their peak vegetative stage, resulting in slightly reduced plant height readings at harvest. The greater height observed in the sole maize treatment (T_2) was likely due to the absence of interspecific competition, particularly from the shorter soybean plants, allowing better light interception and resource utilization. However, maize plants in intercropped treatments also exhibited appreciable height, especially in T_3 (2S:2M) and T_7 (4S:2M), possibly due to an effective spatial arrangement that enhanced light capture and nutrient use efficiency under intercropping conditions.

Regarding dry matter accumulation, T_2 had the highest values at 30 (15.35 g) and 90 DAS (154.02 g), as well as at harvest (164.77). However, at 60 DAS, the dry matter accumulation was higher in T_2 (43.80 g) and was statistically on par with T_5 (40.25 g) and T_7 (42.73 g) (Table 3). A possible reason for the increased plant height and dry matter accumulation in intercropped treatments could be the nitrogen-fixing ability of soybean. The higher soybean density in these treatments likely contributed to increased nitrogen availability for maize, enhancing its growth and overall performance (29, 35). The maizes' crop growth rate (CGR) exhibited a marked increase from the 30 - 60 DAS interval to the 60-90 DAS interval across all treatments. Intercropping had no significant influence on CGR. During 30–60 DAS, CGR ranged from 5.66 to 7.88 g m^{-2} day^{-1}, while during 60–90 DAS, it increased to 21.51 to 29.39 g m^{-2}day^{-1}. Higher CGR in intercropping at early stages may be due to nitrogen sharing from soybean. In contrast, the absence of competition in sole maize likely contributed to its superior CGR at later stages.

Effect of row patterns on yield attributes of maize

Intercropping maize with soybean did not improve yield attributes compared to sole maize cultivation (Table 4). The highest yield parameters, including the number of cobs per plant (1.81), cob weight per plant (277 g) and seed weight cob^{-1} (165.75 g), were observed in the sole maize treatment (T_2). Additionally, T_2 recorded longer cobs (25.87 cm), which were statistically on par with T_4 (24.13 cm), T_5 (23.70 cm) and T_6 (23.28 cm) and had a higher number of seeds per cob (555), which was on par with T_3 (522.25) and T_4 (529.75). Lower yield attributes in intercropped treatments, such as fewer cobs per plant and reduced seed weight per cob, were likely due to increased competition from the dense soybean population. This led to greater competition for nutrients, space and other resources, particularly during the peak growth stage of maize. As a result, maize plants faced nutrient limitations, leading to poorer yield performance and reduced dry matter allocation to the seeds. These findings align with previous research (29, 34, 36).

Effect of row patterns on yield and harvest index of maize

The grain and stover yields were significantly higher in sole maize than in intercropped systems, with 5202.45 kg ha^{-1} and 8693.50 kg ha^{-1}, respectively (Table 5). This was likely due to the optimal plant population and the absence of competition for nutrients, water and sunlight. Among the intercropping treatments, T_4 recorded the highest grain yield (4006 kg ha^{-1}), while T_3 produced the highest stover yield (6023 kg ha^{-1}). This could be due to factors like increased plant height, a greater number of leaves and improved yield attributes (32). Additionally, the presence of soybean may have contributed to better nutrient availability by fixing atmospheric nitrogen and enhancing maize growth. However, maize grain yield declined as the proportion of soybean rows increased. This trend aligns with previous research (36, 33). A higher harvest index was observed in T_4 (47.58 %), which was statistically at par with T_6 (46.04 %) and T_7 (47.23 %). A reduction in maize grain yield due to intercropping has also been documented in

Table 4. Effect of row patterns on yield attributes of maize

Treatments	No. of cobs per plant	Cob weight per plant (g)	Cob Length (cm)	No. of seeds per cob	Seed weight per cob (g)
T_2 (Sole Maize)	1.81^a	277.00^a	25.87^a	555.00^a	165.75^a
T_3 (2S:2M)	1.40^b	197.75^c	21.20^c	522.25^a	128.00^b
T_4 (3S:1M)	1.45^b	231.25^b	24.13^{ab}	529.75^a	131.25^b
T_5 (3S:2M)	1.38^b	189.50^c	23.70^{abc}	439.50^b	125.50^b
T_6 (4S:1M)	1.40^b	210.50^{bc}	23.28^{abc}	344.75^c	112.50^b
T_7 (4S:2M)	1.23^b	182.00^c	22.43^{bc}	395.50^{bc}	116.00^b
SE(m)±	0.08	10.40	0.84	22.57	8.58
CD (p=0.05)	0.24	31.37	2.54	68.03	25.88

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant

Table 5. Effect of row patterns on yield of soybean and maize

Treatments	Soybean Yield (kg ha^{-1})			Maize Yield (kg ha^{-1})		
	Seed Yield	Stover Yield	HI (%)	Grain Yield	Stover Yield	HI (%)
T_1 (Sole soybean)	1155.50^a	1723.25^a	43.55^a	-	-	-
T_2 (Sole maize)	-	-	-	5207.75^a	8693.50^a	37.48^b
T_3 (2S:2M)	613.75^c	788.00^b	43.73^a	3863.75^b	6023.00^b	39.08^b
T_4 (3S:1M)	775.00^b	1688.75^a	31.56^b	4006.25^b	4426.50^c	47.58^a
T_5 (3S:2M)	633.50^c	1504.50^a	28.26^b	3650.00^{bc}	5530.00^b	39..75^b
T_6 (4S:1M)	819.25^b	1711.75^a	32.24^b	3376.75^c	3968.50^c	46.04^a
T_7 (4S:2M)	790.50^b	1691.25^a	31.67^b	3590.50^{bc}	4070.00^c	47.23^a
SE(m)±	29.15	123.19	1.94	154.13	357.65	1.82
CD (p=0.05)	87.87	371.35	5.85	464.61	1078.09	5.51

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant

other studies (27, 33, 38).

Correlation analysis among biometric observations

Correlation analysis among growth parameters, yield attributes and yields in soybean and maize intercropping systems was depicted in Fig. 2. In soybean, grain yield (GY) showed strong positive correlations with plant height (PH, r = 0.871), dry matter accumulation (DMA, r = 0.948), crop growth rate (CGR, r = 0.918) and number of pods per plant (nP/Cp, r = 0.944). Moderate positive correlations were observed with seed index (SI, r = 0.754), number of seeds per pod (nS P/C, r = 0.536) and stover yield (SY, r = 0.584). Harvest index (HI) has a moderate negative correlation with grain yield (r = -0.578). While seed size and seed count per pod have influenced yield, they have played a lesser role than overall growth and biomass.

In soybeans, grain yield has been positively associated with vegetative traits, indicating that robust plant growth enhances the yield potential. Increased plant height, biomass accumulation and growth rate have supported higher grain yields through improved resource capture and utilization (39). The number of pods per plant is a key reproductive trait positively linked to yield, while seeds per pod and seed size play supportive but lesser roles. Overall, yield is more dependent on total biomass production than on the efficiency of biomass partitioning to grains, highlighting the importance of robust plant growth in driving higher yields (40).

In maize, plant height positively correlated with grain yield (r = 0.725). Dry matter accumulation showed a strong positive correlation with grain yield (r = 0.926), crop growth rate (r = 0.957) and the number of cobs per plant (r = 0.924). The number of seeds per cob had a moderate positive correlation with grain yield (r = 0.774) and seed index (r = 0.671). Stover yield demonstrated a strong positive correlation with grain yield (r = 0.905). The harvest index exhibited a weak positive correlation with grain yield (r = 0.399).

In maize, plant height shows a moderate correlation with grain yield. In contrast, dry matter accumulation and crop growth rate display strong positive correlations, underscoring the importance of vegetative growth and resource utilization for yield. The number of cobs per plant is also positively correlated with yield, highlighting the value of reproductive productivity. Although seed number per cob and index have moderate correlations, their impact on yield is secondary to biomass-related traits. The strong correlation between stover yield and grain yield further emphasizes that high biomass production is key for yield maximization in maize, with the harvest index showing a slight positive influence. Similar results have been reported in other studies (39, 41).

Principal component analysis (PCA)

Principal component analysis among biometric observations such as, growth parameters, yield attributes and yields in soybean maize intercropping systems was presented in Fig. 3. The PCA biplot shows that grain yield (GY) in soybean is strongly associated with crop growth rate (CGR) and dry

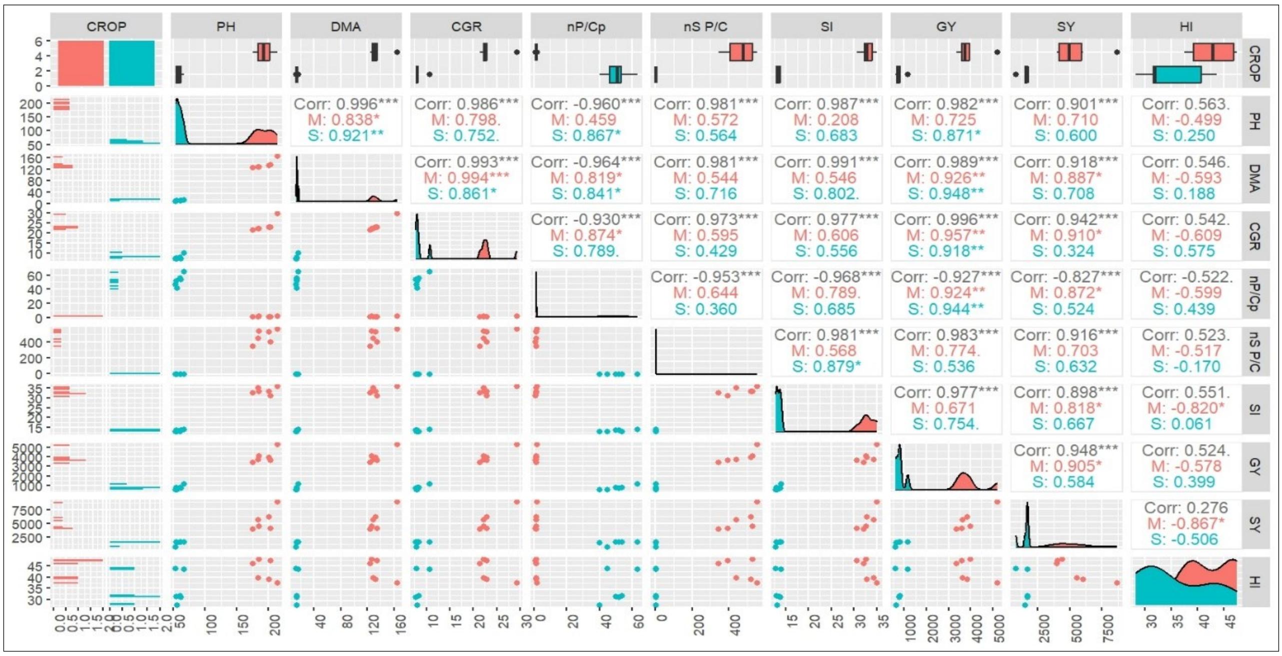
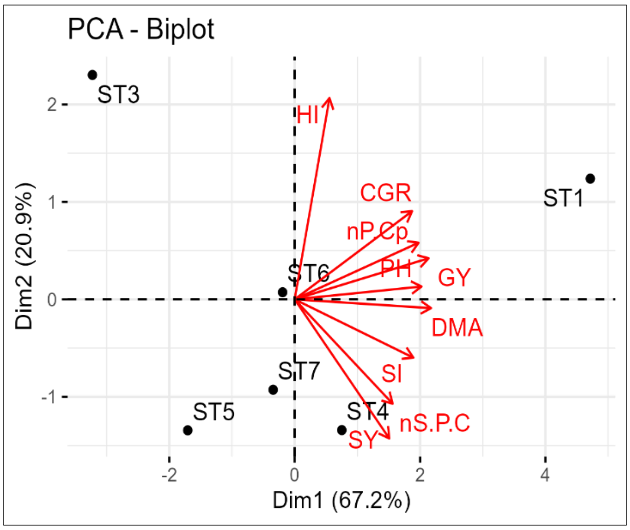
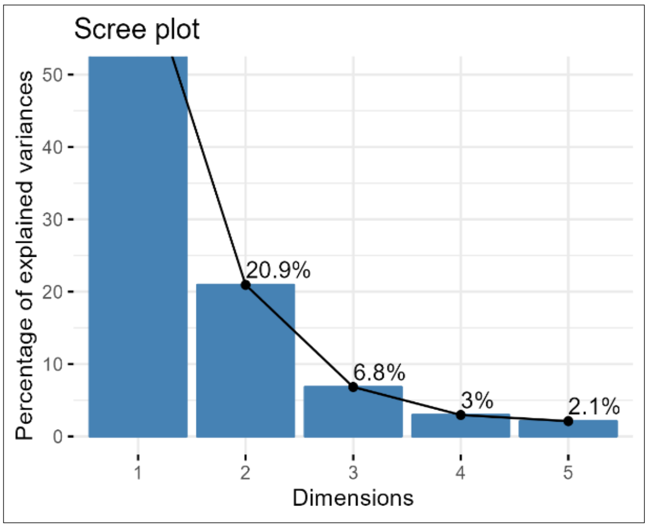


Fig. 2. Correlation analysis among the different biophysical parameters of soybean and maize.

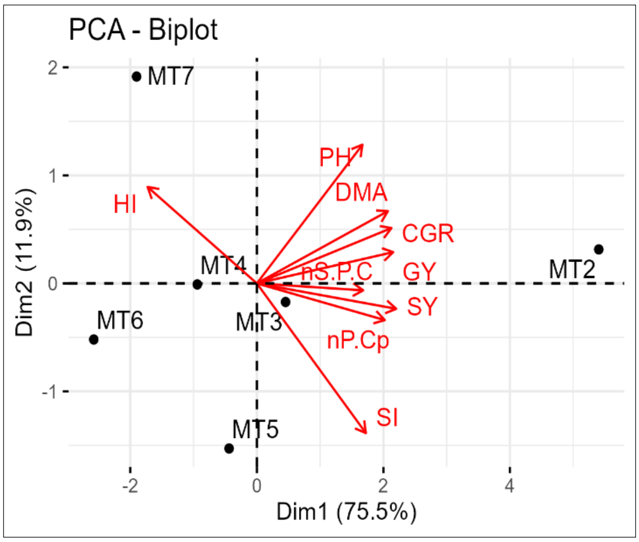
(**Note:** PH: plant height; DMA: dry matter accumulation; CGR: crop growth rate; nP/Cp: number of pod or cob per plant; nS P/C: number of seeds per plant or cob; SI: seed index; GY: grain yield; SY: seed yield and HI: harvest index)



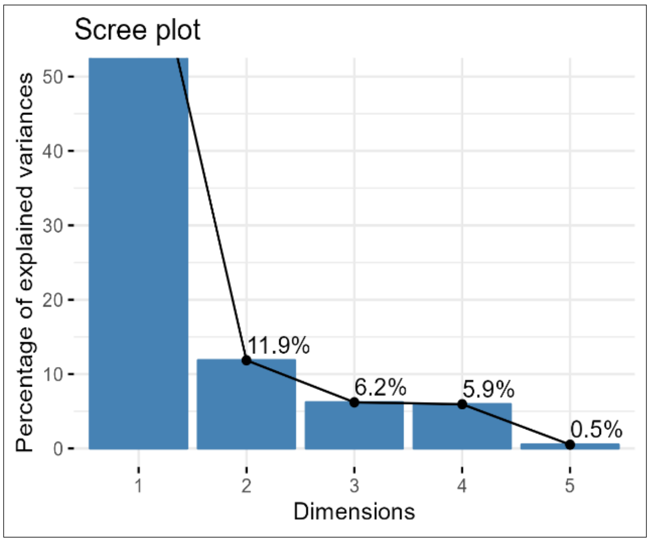
a. PCA biplot of soybean



b. Scree plot of soybean



c. Biplot of maize



d. Scree plot of maize

Fig. 3. Principal component analysis of: a-b) Soybean; c-d) Maize.

Note: ST- Soybean treatment; MT1– Maize treatment.

matter accumulation (DMA), indicating that higher biomass and rapid growth contribute significantly to yield. Traits like the number of pods per plant (nP/Cp) and plant height (PH) also positively correlate with yield, though somewhat. Seed index (SI) and stover yield (SY) show moderate associations. In contrast, harvest index (HI) aligns primarily with the second principal component (Dim2), which explains 20.9 % of the total variance, suggesting a distinct or minimal influence on yield compared to other traits. The score plot and biplot of the PCA analysis indicate that ST1 (sole soybean) aligns most strongly with key growth and yield parameters, followed by ST4. The scree plot reveals that PC1 accounts for 67.2 % of the total variation, while PC2, PC3, PC4 and PC5 explain 20.9 %, 6.8 %, 3 % and 2.1 %, respectively. Since PC1 captures the largest share of variance, ST1 and ST4 exhibit the strongest association with traits linked to soybean growth and yield performance, highlighting their potential relevance in influencing these parameters.

The PCA biplot shows that grain yield in maize was strongly associated with dry matter accumulation and crop growth rate, indicating that higher biomass and rapid growth contribute significantly to yield. Parameters like the seed index, number of cobs per plant and plant height also positively correlate with yield, though to a lesser extent. In contrast, the harvest index (HI) showed a negatively correlated and minimal influence on yield compared to other parameters aligning primarily with the first principal component (Dim1). The score plot and biplot of the PCA analysis showed that among all the treatments applied, MT1, which was sole maize, had the highest impact on the growth and yield parameters. The scree plot of the PCA analysis showed three principal components, with PC1 describing 75.5 % variation. PC2, PC3, PC4 and PC5 explained 11.9, 6.2, 5.9 and 0.5 % of the variance, respectively. Since PC1 explained more than 75 % variance, we can conclude that MT2, with the highest value, followed by MT3 was the most effective for maize growth and yield (39).

Effect of row pattern on quality parameters of soybean and maize intercropping

Effect of row pattern on oil content and oil yield of soybean

Intercropping with maize did not significantly affect the oil content of soybean seeds, but it significantly impacted oil yield (Table 6). Among the treatments, sole soybean (T_1) produced the highest oil yield (16303.50 kg ha^{-1}), followed by T_6 (11232.25 kg ha^{-1}) which was at par with T_4 (10645 kg ha^{-1}) and T_7 (9769.25 kg ha^{-1}). This was likely due to the higher seed yield in sole soybean, resulting from reduced competition from maize and better nutrient availability due to reduced competition from maize. The higher oil content in sole soybean could be attributed to improved nutrition, as fewer competing plants allowed better nutrient uptake. Additionally, soybean seed oil percentage is influenced by light absorption. Taller maize plants create more shade, which can lower oil content, while better light exposure enhances it (28).

Effect of row pattern on crude protein content of soybean and maize

The crude protein percentage in soybeans depends on the nitrogen content of the seeds. A higher crude protein content (38.87 %) was recorded in T_3, which was statistically at par with T_1 (38.17 %), T_7 (37.61 %) and T_4 (37.30 %) (Table 7). Lower crude protein content in soybean may be due to shading from taller maize plants, which limits nutrient availability in the seeds and reduces protein accumulation (12, 28, 42).

However, intercropped maize showed higher protein content than sole maize. Among the intercropped treatments, T_4 recorded a higher crude protein content (9.5 %), statistically being at par with T_3 (8.80 %), T_6 (8.80 %) and T_7 (8.705) (Table 7). This increase in protein content in maize may be due to improved nitrogen uptake, as soybean aids in atmospheric nitrogen fixation, making more nitrogen available for maize growth. Previous studies (27) also support that crude protein content is highest in sole maize, followed by the 4S:2M intercropping system.

Effect of row pattern on competitive indices of soybean and maize intercropping

The value of LER suggested that the result was above unity in all the intercropping situations, indicating a yield advantage over the sole crops. The highest LER (1.44) was observed under T_4 (Fig. 4). The higher LER might be due to the better performance of both crops due to the minimal competition for overall growth resources, which are exceptionally light, owing to the greater complementarity of soybeans (33). The highest LER index observed under T4 indicated that maize and soybean crops can provide much

Table 6: Effect of intercropping of soybean and maize on oil content and oil yield of soybean

Treatments	Oil content (%)	Oil yield (kg ha^{-1})	Crude protein content (%)	
			Soybean	Maize
T_1 (Sole soybean)	14.10	16303.50^{a}	38.71^{ab}	_
T_2 (Sole maize)	_	_	_	7.40^{c}
T_3 (2S:2M)	13.55	8320.50^{c}	38.87^{a}	8.81^{a}
T_4 (3S:1M)	13.67	10645.00^{b}	37.30^{abc}	9.50^{a}
T_5 (3S:2M)	13.80	8732.00^{c}	36.92^{bc}	8.40^{bc}
T_6 (4S:1M)	13.72	11232.25^{b}	36.27^{c}	8.81^{a}
T_7 (4S:2M)	12.40	9769.25^{bc}	37.61^{abc}	8.70^{a}
SE(m)±	0.44	662.53	0.56	0.34
CD (p=0.05)	NS	1729.54	1.68	1.05

T_1 = (sole soybean); T_2 = (sole maize); T3 (2S:2M) = 2 rows of soybean:2 rows of maize; T_4 (3S:1M) = 3 rows of soybean:1 row of maize; T_5 (3S:2M) = 3 rows of soybean:2 rows of maize; T_6 (4S:1M) = 4 rows of soybean:1 row of maize; T_7 (4S:2M) = 4 rows of soybean:2 rows of maize; NS: Non-significant

Table 7. Effect of intercropping of soybean and maize on competitive indices

Treatments	Competitive indices								Economic Efficiency	
	LER	ASM	AMS	KSM	KMS	K	MAI (Rs ha^{-1})	SEY (kg ha^{-1})	Net Return	B:C Ratio
T_1 (sole soybean)	-	-	-	-	-	-			57292	2.23
T_2 (sole maize	-	-	-	-	-	-	-	1157	58708	2.29
T_3 (2S:2M)	1.27	-0.11	+0.11	1.13	2.87	3.25	28173	1437	86461	2.88
T_4 (3S:1M)	1.44	-0.55	+0.55	0.68	10.00	6.78	45795	1665	103123	3.21
T_5 (3S:2M)	1.25	-0.17	+0.17	0.81	3.51	2.84	26001	1444	82965	2.76
T_6 (4S:1M)	1.36	-0.47	+0.47	0.61	7.38	4.48	37393	1569	94378	3.01
T_7 (4S:2M)	1.37	-0.17	+0.17	1.08	4.44	4.80	38609	1589	96340	3.07
SE(m)±	-	-	-	-	-	-	-	31.57	2841.97	0.06
CD (*p*=0.05)	-	-	-	-	-	-	-	93.82	8443.95	0.18

T1= (sole soybean); T2= (sole maize);T3 (2S:2M)= 2 rows of soybean: 2 rows of maize; T4 (3S:1M)= 3 rows of soybean:1 row of maize; T5 (3S:2M)= 3 rows of soybean: 2 rows of maize; T6 (4S:1M)= 4 rows of soybean: 1 row of maize; T7 (4S:2M)= 4 rows of soybean: 2 rows of maize; LER: Land equivalent ratio; ASM: Aggressivity of soybean over maize; AMS: Aggressivity of maize over soybean; KSM: Co-efficient of soybean in the presence of maize; KMS: Co-efficient of maize in the presence of soybean; K: Product of the co-efficient; MAI: Monetary advantage index; SEY: Soybean equivalent yield; B:C – Benefit cost ratio

higher income when intercropped together rather than planted as sole crops (32, 43-45).

The effect of treatments on aggressivity revealed that maize was more aggressive over soybean in all the intercropping situations. Soybean consistently exhibited a negative aggressivity value across treatments, indicating it was less competitive species, whereas maize, with positive values, dominated the intercropping system. Thus, soybean proved to be less competitive than maize. It indicated that during the symbiotic period of maize and soybean, soybean was at a competitive disadvantage in the intercropping system and maize emerged as a more competitive crop (46). The highest aggressivity of maize (+0.55) was recorded under T_4 (Table 7). It was observed that the aggressivity of maize crops towards soybeans reduced with an increase in maize rows in the respective treatments. Similar results of the dominancy of maize in intercropping with soybean were also reported in earlier studies (47, 48).

A perusal of Table 7 revealed that across all intercropping treatments, the value of K_{Maize} consistently exceeded that of $K_{Soybean}$. This indicated maizes' prevalence or greater competitiveness than soybean within the intercropped setup. The highest K value for maize was recorded under T_4. Furthermore, the co-efficient (K) product was more significant than unity irrespective of the treatments, which revealed a yield advantage in intercropping. The maximum value (6.78) of K was found under T4 (3S:1M) followed by T_7, signifying that these specific treatments gave the most significant advantages in terms of yield among all intercropping treatments (47).

The monetary advantage index depicted economic benefit across all the intercropping treatments in contrast to sole cropping. The highest financial gain (45795 Rs ha^{-1}) was obtained in T_4 (Fig 4). Treatments with higher monetary advantages indicated their superior profitability compared to others. Similar results reported earlier highlighted the more significant financial benefits of

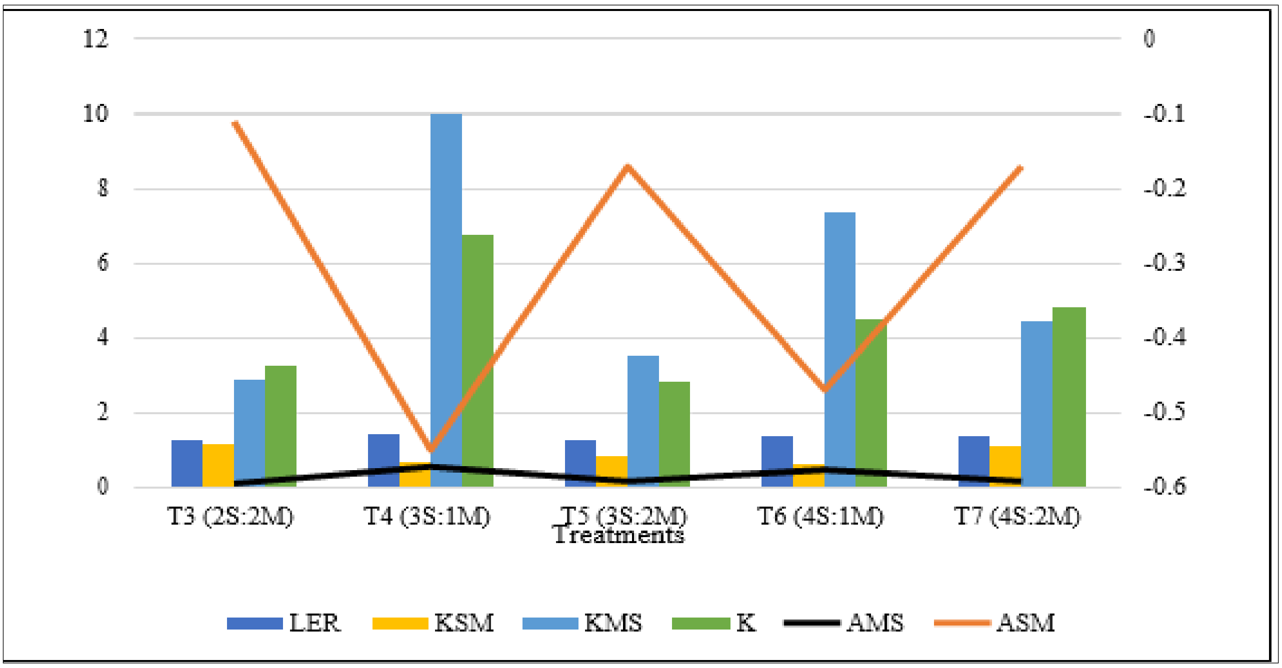


Fig. 4. Effect of intercropping of soybean and maize on LER, aggressivity and RCC.

intercropping systems in comparison to monoculture (47, 48),

Intercropping treatments recorded higher equivalent yields compared to sole soybeans. The maximum soybean equivalent yield (1665 kg ha^{-1}) was recorded under T_4 and statistically at par with T_7. The higher yield of the crops might be the reason for the higher equivalent yield obtained under the intercropping system.

Effect of row pattern on economic parameters

All intercropped treatments gave higher net return over sole (Fig. 5). The highest net return (Rs 103123) and benefit-cost ratio (3.21) were recorded under T_4 (Table 7). Intercropping treatments with more soybean rows resulted in significantly higher economic returns (34). The increased yields of both the component crops, couples with lower cost of cultivation, contributed to these higher net returns. Similarly, the reduced cost of cultivation and higher net return led to a higher benefit-cost ratio in these treatments (33).

Conclusion

This study demonstrated that the 3S:1M maize-soybean intercropping system significantly enhances resource use efficiency, productivity and profitability. Its Land Equivalent Ratio (LER) of 1.44 indicates a clear yield advantage over sole cropping. Economic analysis further supports the systems' viability by revealing the highest net returns and benefit-cost ratio, highlighting its potential as an optimal strategy for smallholder farmers in resource-limited regions. These findings emphasize the promise of this intercropping model in advancing sustainable agricultural practices and call for further research into its long-term impacts on soil fertility and overall ecological resilience, ultimately encouraging stakeholders to adopt and promote this innovative approach to strengthen food security and agricultural sustainability worldwide.

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Authors' contributions

MP performed the experiments and contributed to the writing of the manuscript. TS was involved in designing the research, performing the experiments, and writing the manuscript. HN contributed to the research design and participated in revising and correcting the manuscript. NK was responsible for designing the research and contributed to the revision and correction of the manuscript. LS assisted in the conceptualization of the research and took part in revising and finalizing the manuscript. PK contributed to the manuscript writing and was actively involved in its revision and correction. CS participated in the writing of the manuscript and contributed to its revision and final corrections. All authors have contributed to different writing sections, reviewing, correction, and statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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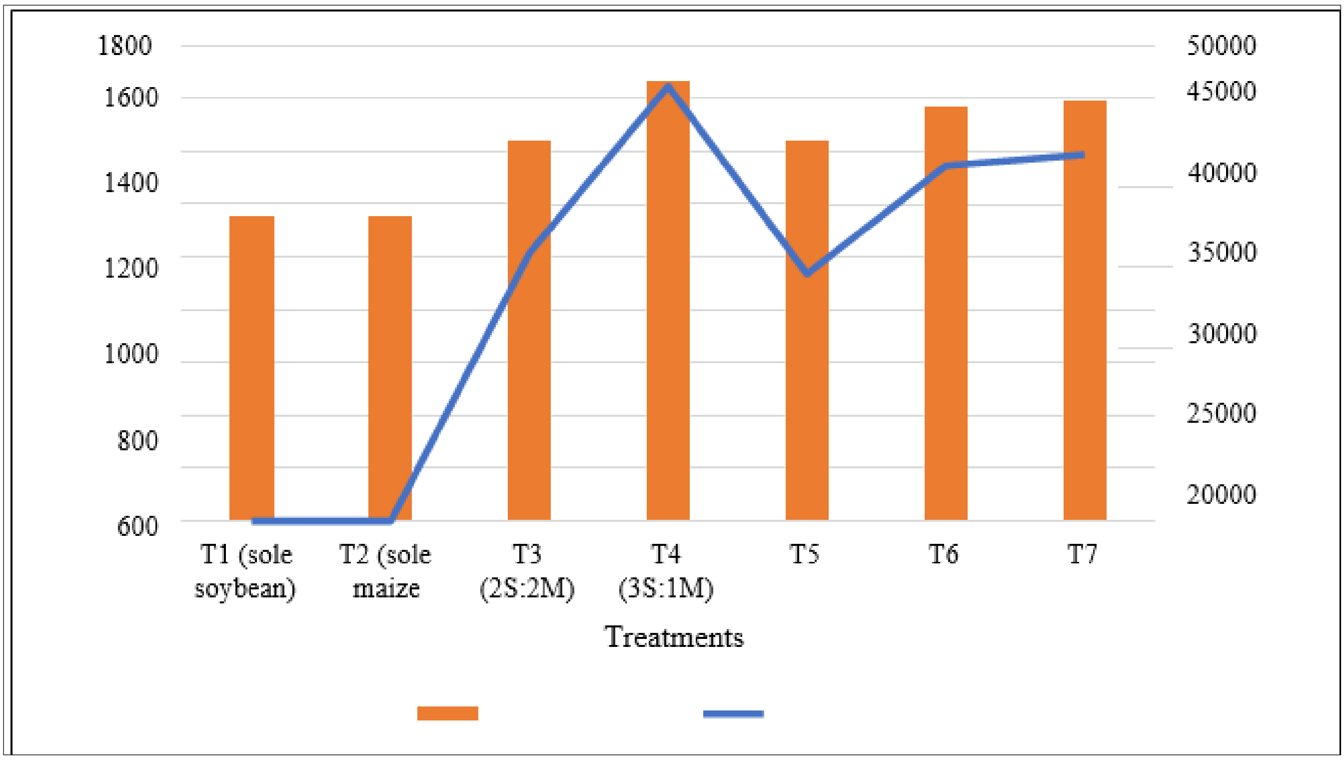

Fig. 5. Effect of intercropping of soybean and maize on soybean equivalent yield (SEY) and monetary advantage index (MAI).

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