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RESEARCH ARTICLE

Optimizing soybean productivity through land configuration and integrated nutrient management under subtropical

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Abstract

A field experiment was conducted during the *Kharif* season of 2024 at Lovely Professional University, Punjab, to evaluate the effect of land configuration and nutrient management on the growth, yield and quality of soybean (*Glycine max* L.). The experiment followed a factorial randomized block design (FRBD) with two land configurations: flatbed (L_1) and ridge and furrow (L_2). Eight nutrient management treatments (N1 to N8) including various combinations of nitrogen (N), phosphorus (P) and farmyard manure (FYM). Soybean variety SL958 was used and data were collected on growth parameters, yield components and seed protein content. Ridge and furrow configuration significantly improved plant growth and seed yield compared to the flatbed system. The best performance for growth, yield attributes and protein content (40.00 %) were observed under 75 % N + 25 % FYM + 75 % P (N_8), followed by 75 % N + 100 % P (N_4), while the control showed the lowest performance across all parameters. Significant interaction effects confirmed that combining ridge and furrow with balanced nutrient application optimally enhances soybean growth, yield and quality. The study highlights the potential of ridge and furrow land configuration combined with integrated nutrient management to maximize soybean yield and quality in sandy clay loam soils under subtropical conditions.

Keywords: integrated nutrient management; land configuration; nitrogen and phosphorus fertilization; responsible crop production and zero hunger

Introduction

Oilseed crops supply fats and oils, which are essential for the human diet, comprising around 40 % of the average person's calorie requirement. India is one of the leading producers and consumers of vegetable oils globally. Oilseeds have been the foundation of India's agricultural economy. The Indian vegetable oil economy ranks as the fourth largest globally, following the United States, China and Brazil (1). In Indian agriculture, oilseeds hold the second-largest area and production share after food grains, making them central to the country's Agrarian economy.

In India, it is the predominant oilseed crop, encompassing an area of 13.26 million hectares and yielding 13.06 million tons, with an average productivity of 985 kg ha^{-1} (2). Soybean is one of nature's most efficient protein sources and a significant component of dietary protein for millions, yielding at least three times more useable protein than rice, wheat and maize crops (3). Unlike most other plant proteins, soybean contains essential amino acids such as methionine and tryptophan, enhancing their nutritional profile. Soybean, containing approximately 40-42 % protein and 18-22 % oil, is emerging as one of the fastest-growing oil seed crops globally (4). In India, it plays a crucial role in meeting dietary protein and oil demands through value-added products and edible oils.

Despite the continual expansion of soybean agriculture over the past decade, its productivity has not observed a corresponding increase due to unpredictable rainfall patterns, including extremes such as droughts and waterlogging (5). In heavy to medium soils, both drought (soil cracking) and excessive rainfall (waterlogging) resulted in suboptimal plant growth and decreased production. Consequently, open furrow cultivation may serve dual purposes: conserving soil moisture during dry periods and facilitating drainage of excess water in waterlogged conditions.

Soybean has gained popularity due to low cultivation costs, short duration and favorable market prices (6). Over the past 4-5 years, erratic rainfall, a gradual rise in temperature during the reproductive cycle and the occurrence of dry spells or excessive rainfall during critical growth stages (flowering, pod formation and pod filling) have induced water stress (due to either drought or waterlogging), adversely affecting both crop growth and agronomic operations in the field. This may explain the reduced seed output in this crop. Topography significantly affects root and nodule development in soybean (7).

Flatbed cultivation often leads to waterlogging and poor aeration, which hampers plant growth and yield. Moreover, imbalanced and excessive use of chemical fertilizers has contributed to declining soil fertility and productivity (8). Long term use of inorganic fertilizers has deteriorated soil health and productivity. The many experiments conducted in various locations have clearly demonstrated the persistent necessity to combine organic manures with inorganic fertilizers to ensure sustainable production and the preservation of soil productivity and fertility. Currently, the costs related to fertilizers and manures are significantly higher, hence increasing cultivation costs and diminishing net returns per unit area. Thus, integrating organic and inorganic nutrient sources presents a viable strategy to improve soil health, crop yield and economic returns. In this context, the present study was undertaken to investigate the combined effect of land configuration and nutrient management on the growth, yield and quality of soybean.

Materials and Methods

The field experiment was carried out during the *Kharif* season of 2024 at the Agronomy Research Farm, Lovely Professional University, Phagwara, Punjab (31.25°N, 75.00°E; altitude 300 m above mean sea level), as shown in Fig. 1. Soil samples were collected before the start of the experiment from the depth of 0-15 cm to analyses mechanical composition and chemical properties of soil. The experimental field had a sandy clay loam soil texture with an alkaline reaction (pH = 8.1; EC = 0.15 dS m^{-1}).

The experiment was carried out during *Kharif* of 2024 (June-November). Weekly meteorological parameters including mean maximum and minimum temperature, relative humidity and rainfall received from the Agromet observatory of the School of Agriculture, LPU, Phagwara during the cropping season are presented in Fig. 2. The mean maximum temperature ranged between 44.28 °C and 22.67 °C and the mean minimum temperature ranged between 29.57 °C and 13 °C, the mean relative humidity ranged between 40.28 % and 93.17 %. The total *Kharif* season rainfall received during the cropping season was 83.7 mm.

The experimental field was prepared by ploughing twice with a cultivator, followed by rotavator and leveling. Two land configuration treatments were implemented: (i) flatbed, where the land was leveled uniformly and (ii) ridge and furrow, where ridges 45 cm wide were constructed with furrows in between. The experiment was laid out in a factorial randomized block design (FRBD) with three replications. Factor A included two land configurations: L1 - flatbed and L2 - ridge and furrow. Factor B consisted of eight nutrient management treatments: N_1 - control, N_2 - 25 % N + 100 % P, N_3 - 50 % NP, N_4 - 75 % N+ 100 % P, N_5 - Only FYM-RDF, N_6 - 25 % N + 25 % P + 75 % FYM, N_7 - 50 % N + 50 % P + 50 % FYM, N_8 - 75 % N + 25 % FYM + 75 % P.

The recommended dose of FYM was 10 t ha^{-1}. The RDF for soybean was 32 kg N and 80 kg P_2O_5 ha^{-1}, supplied through 70 kg urea and 500 kg single superphosphate. The soybean variety SL958 was used. Seeds were inoculated with Rhizobium culture at 250 g ha^{-1} and air-dried in shade for 30 min before sowing to prevent desiccation injury. Sowing was carried out on June 13, 2024, using a spacing of 45 cm between rows and 5 cm between plants, followed by light irrigation.

Growth parameters recorded included plant height, number of branches per plant, number of leaves, leaf area, number of root nodules per plant, dry matter weight per plant, stem girth and chlorophyll index (SPAD). Observations were taken from five randomly selected plants per plot. Leaf area was calculated using the linear method (length × maximum width). Nodule counts were recorded at 50 % flowering.

Yield parameters including number of pods per plant, pod length (cm), seeds per pod, test weight, seed yield (kg ha^{-1}), stover yield (kg ha^{-1}) and harvest index were recorded on a per plot at harvest. Seed protein content was estimated by multiplying the nitrogen percentage with a conversion factor of 6.25 (9).

Statistical analysis

The experimental data obtained on various factors were statistically analyzed using analysis of variance (ANOVA) techniques for Factorial RBD. The OPSTAT programme created by the CCS Haryana Agricultural University, Hisar, was used to compare treatments (10). The F test was used to determine significance (11). When the F test was significant, the critical difference (CD) was provided.

Results and Discussion

Effect of land configuration and nutrient management on growth attributes

Plant height (cm)

The plant height showed significant variation across different land configurations and nutrient management techniques as depicted in Table 1. The ridge and furrow configuration showed a significantly higher plant height (69.325 cm) than the flat bed configuration (63.48 cm). The increase in plant height under ridge and furrow might be due to better soil aeration, improved root development and effective moisture retention. The tallest plant height (76.815 cm) was recorded in treatment N_8, which was significantly superior to all other treatments. This may result through adequate and balanced supply of nitrogen and phosphorus, which are essential for vegetative growth and cellular elongation. The minimum plant height (55.82 cm) was observed in the control treatment, indicating that nutrient deficiencies restrict plant growth. The interaction between land configuration and nutrient management was significant (CD = 1.850, $p < 0.05$), indicating that plant height was improved under the combination of ridge and furrow with balanced nutrient management as depicted in Table 2. The tallest plants for the broad bed furrow (BBF) method are in soybeans during the rainy season, followed by the RAF (Ridges and furrows) and flatbed method (12). The maximum plant height was registered with the application rate of 118 kg P_2O_5 ha^{-1} (13).

Leaf area (cm^2)

The leaf area was significantly larger in ridge and furrow (704.795 cm^2) than in flatbed (624.247 cm^2). This increase might be due to improved nutrient absorption and water accessibility in ridge and furrow conditions, which facilitate more leaf expansion. The highest leaf area (809.405 cm^2) was recorded under the treatment of N_8, followed by N_4 (788.10 cm^2) and N_7 (744.53 cm^2). The increase of leaf area in these treatments may result from the synergistic interactions of nitrogen, phosphorus and farmyard manure, enhancing photosynthetic efficiency. The minimum leaf area (488.80 cm^2) was noticed in the control, indicating lack of nutrients for proper development of leaves. The interaction effect between land configuration and nutrient management was significant (CD = 2.90), indicating that the ridge and furrow system when combined with optimal nutrients management promotes canopy development (14).

Table 1. Effect of land configuration and nutrient management on plant height, leaf area, number of branches, no. of leaves and stem girth of soybean

Treatments	Plant height (cm)	Leaf area (cm^2)	No. of branches $plant^{-1}$	No. of leaves $plant^{-1}$	Stem girth (cm)
		Land configuration			
L_1- Flat bed	63.48	624.247	6.435	41.89	7.73
L_2- Ridge & Furrow	69.325	704.795	7.091	47.64	8.44
SE(d)	0.319	0.50	0.056	0.28	0.063
CD(p = 0.05)	0.654	1.025	0.115	0.571	0.130
		Nutrient management			
N_1- Control	55.82	488.80	5.04	31.42	6.64
N_2- 25 % N + 100 % P	64.36	653.42	6.70	43.26	7.94
N_3- 50 % NP	64.940	641.99	6.48	43.39	7.99
N_4- 75 % N + 100 % P	74.142	788.10	7.83	53.91	8.92
N_5- Only FYM	59.66	541.510	5.55	34.48	7.0
N_6- 25 % N + 25 % P + 75 % FYM	64.96	648.717	6.67	44.137	8.02
N_7- 50 % N + 50 % P + 50 % FYM	70.78	744.53	7.7	50.30	8.812
N_8- 75 % N + 25 % FYM + 75 % P	76.815	809.405	8.18	56.43	9.36
SE(d)±	0.637	0.99	0.112	0.556	0.127
CD (p < 0.05)	1.308	2.05	0.229	1.142	0.26

Table 2. Interaction between land configuration and nutrient management on plant height, leaf area, number of branches, no. of leaves and stem girth of soybean

Interaction b/w LN	Plant height (cm)	Leaf area (cm^2)	No. of branches $plant^{-1}$	No. of leaves $plant^{-1}$	Stem girth (cm)
L_1N_1	54.00	452.54	4.97	30.59	6.54
L_1N_2	60.00	584.53	6.20	37.21	7.38
L_1N_3	63.52	610.94	6.35	41.33	7.76
L_1N_4	69.97	751.77	7.43	50.38	8.53
L_1N_5	58.01	532.38	5.57	33.26	6.77
L_1N_6	62.27	602.70	6.30	41.15	7.65
L_1N_7	68.32	705.37	7.13	47.33	8.40
L_1N_8	72.28	753.74	7.53	52.25	8.78
L_2N_1	57.63	524.43	5.11	32.25	6.73
L_2N_2	68.72	722.31	7.20	49.31	8.50
L_2N_3	66.36	673.04	6.60	45.44	8.23
L_2N_4	78.31	824.43	8.23	57.43	9.32
L_2N_5	61.32	550.64	5.53	35.70	7.23
L_2N_6	67.65	694.73	7.03	47.13	8.39
L_2N_7	73.24	783.70	8.19	53.27	9.23
L_2N_8	81.35	865.07	8.83	60.61	9.93
SE(d)±	0.901	1.413	0.158	0.787	0.18
CD (p < 0.05)	1.850	2.90	0.324	1.615	0.368

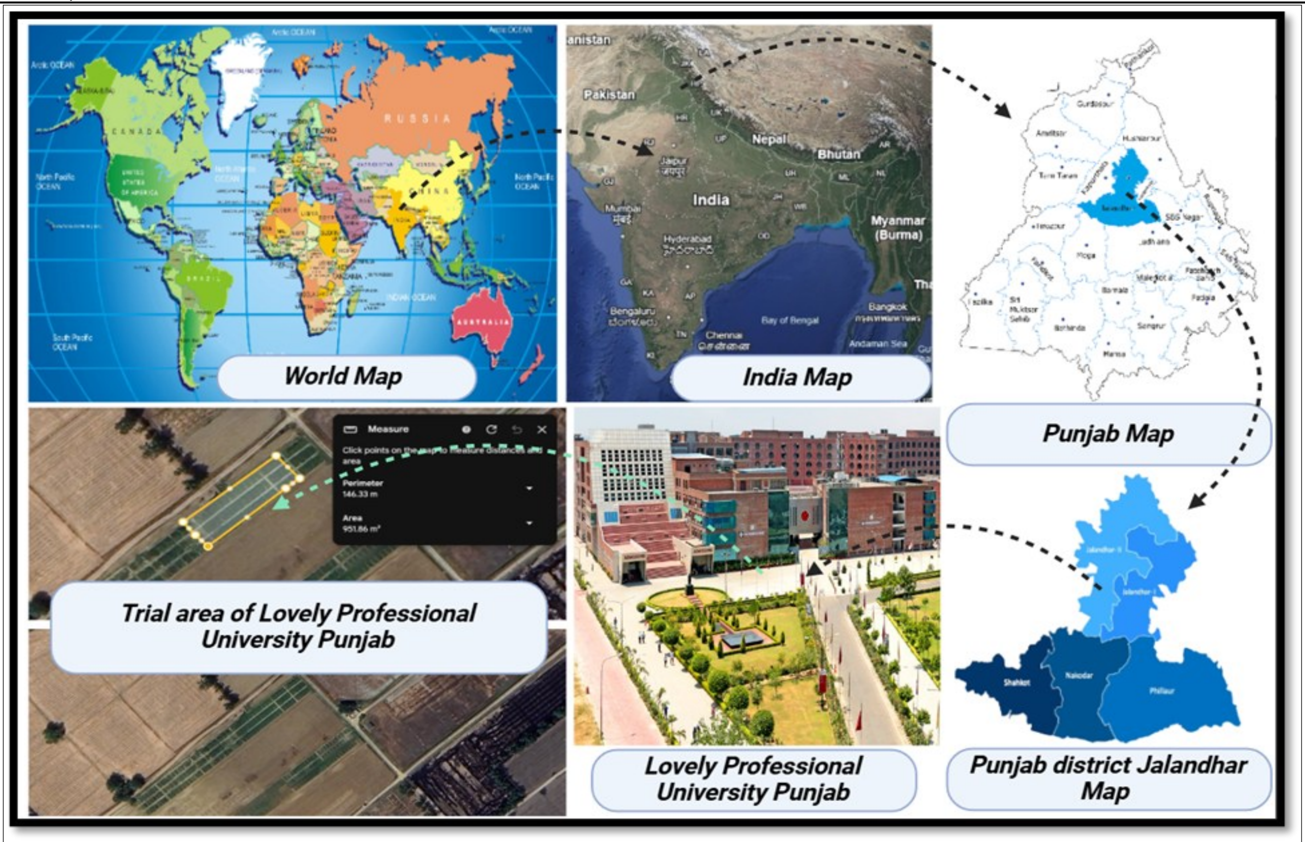

Fig. 1. Geographical coordinates of the experimental location.

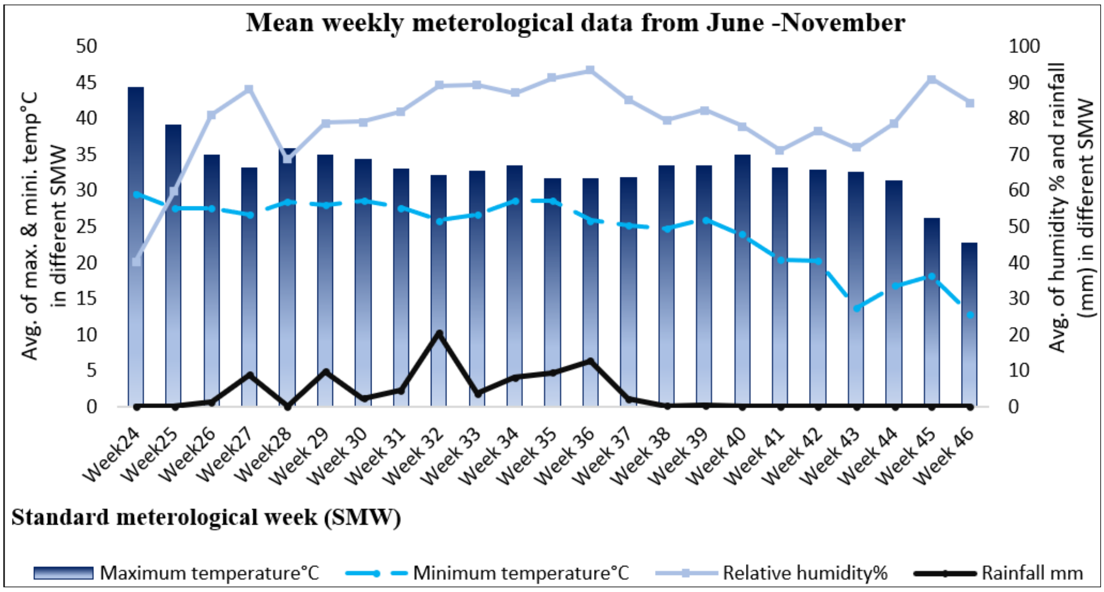

Table 2. Interaction between land configuration and nutrient management on plant height, leaf area, number of branches, no. of leaves and stem girth of soybean

Number of branches plant^{-1}

The ridge and furrow method (7.091 branches plant^{-1}) produced significantly higher branches as compared to the flat bed method (6.435 branches plant^{-1}). This improvement is due to improved soil structure and aeration in the ridge and furrow system, facilitating secondary branch development. In terms of nutrient treatments, N_8 showed the highest number of branches (8.18), followed by N_4 (7.83) and N_7 (7.7). The application of phosphorus, nitrogen and farmyard manure increased lateral development, resulting in increased branch production. In comparison, the control treatment exhibited the lowest number of branches, totaling 5.04. The relationship between land configuration and nutrient management was statistically significant (CD = 0.324), suggesting that the integration of ridge and furrow with N_8 significantly enhanced branching. The highest number of branches per plant of soybean was observed in the BBF and RAF methods during *Kharif* (15).

Number of leaves plant^{-1}

The ridge and furrow method (47.64 leaves plant^{-1}) showed a significantly higher leaf number than the flat bed (41.89 leaves plant^{-1}). The increased number of leaves in ridge and furrow might result from more root proliferation and nutrient absorption, leading to improved vegetative development. The nutrient treatment combining N_8 produced the maximum number of leaves (56.43), followed by N_4 (53.91) and N_7 (50.30). The rise in leaf count in these treatments can be attributed to improved nitrogen availability, essential for chlorophyll production and leaf growth. The control showed the lowest number of leaves (31.42), illustrating the significance of a balanced nutrition supply for optimal leaf development. The interaction between land configuration and nutrient management significantly increased leaf number (CD = 1.615, $p <$ 0.05). The BBF method recorded the highest number of leaves plant^{-1} in soybeans during the rainy season followed by the RF and flatbed method (16).

Stem girth (cm)

The stem girth was significantly higher in the ridge and furrow (8.44 cm) than on the flat bed (7.73 cm), indicating that better stem development is influenced by improved root holding and nutrient availability in the ridge and furrow conditions. The nutrient treatment comprising N_8 resulted in the highest stem girth around 9.36 cm, followed by N_4 at 8.92 cm and N_7 at 8.812 cm. The increased stem girth in these treatments results from the synergistic effects of nitrogen, phosphorus and FYM, which improve stem growth and structural integrity. The control had the lowest stem girth around 6.64 cm, emphasizing the significance of adequate nutrition availability for stem thickness. The interaction effect was statistically significant (CD = 0.368, $p <$ 0.05), suggesting that the combination of ridge and furrow along with appropriate fertilizer management increased stem girth. This result is in conformity with the findings in cowpea (17).

Chlorophyll index (SPAD)

The chlorophyll index showed significant variation across different land arrangements and nutrient treatments. The ridge and furrow (L_2) configuration had a significantly higher SPAD reading of 38.12 in contrast to the flat bed (L_1) configuration, which recorded 28.23 as shown in Table 3. The increased chlorophyll levels in ridge and furrow increased absorption of nutrients and availability of water, thus enhancing photosynthetic efficiency. The highest SPAD value (37.52) among nutrient treatments was observed in N_8, followed by N_4 (36.36) and N_7 (33.72). The least SPAD value (21.69) was recorded in the control treatment (N_1), highlighting the significance of balanced nutrient management in facilitating chlorophyll production. The interaction effect between land configuration and nutrient management was significant (CD = 1.32), indicating that ridge and furrow with appropriate supply of nutrients enhanced chlorophyll concentration (18) as shown in Table 4. The higher SPAD values under N8 and ridge and furrow systems indicate increased chlorophyll synthesis due to improved nitrogen uptake and moisture availability.

Dry matter accumulation (g)

Dry matter accumulation was considerably higher in ridge and furrow (64.58 g) than in flatbed (57.24 g). The increased accumulation in ridge and furrow can be related to higher root growth, resulting in better nutrition and moisture availability. The highest dry matter accumulation (75.42 g) was observed in

Table 3. Effect of land configuration and nutrient management on chlorophyll index, dry matter, nodules plant^{-1}, pod length and seed pod^{-1} of soybean

Treatments	Chlorophyll index (SPAD)	Dry Matter (g)	Nodules Plant^{-1}	No. of Pods plant^{-1}	Pod length (cm)	Seed pod^{-1}
Land configuration						
L_1- Flat bed	28.23	57.24	19.413	46.12	3.95	2.48
L_2- Ridge & Furrow	38.12	64.58	23.671	50.89	4.34	2.71
SE(d)	0.23	0.304	1.17	0.110	0.064	0.027
CD	0.47	0.624	2.51	0.225	0.130	0.054
Nutrient management						
N_1- Control	21.69	46.26	15.81	36.13	3.1	1.85
N_2- 25 % N +100 % P	29.32	58.31	21.28	47.93	4.14	2.58
N_3- 50 % NP	29.46	59.90	23.63	46.39	4.14	2.58
N_4- 75 % N + 100 % P	36.36	7.87	26.43	56.81	4.82	2.95
N_5- Only FYM	24.19	50.43	19.33	39.78	3.43	2.22
N_6- 25 % N + 25 % P + 75 % FYM	29.14	58.77	24.49	46.92	4.0	2.55
N_7- 50 % N + 50 % P + 50 % FYM	33.72	67.32	21.11	54.88	4.57	2.86
N_8- 75 % N +25 % FYM + 75 % P	37.52	75.42	20.26	59.84	5.02	3.2
SE(d)±	0.46	0.61	2.33	0.219	0.127	0.053
CD ($p < 0.05$)	0.94	1.25	5.03	0.45	0.261	0.109

Table 4. Interaction between land configuration and nutrient management on chlorophyll index, dry matter, nodules plant^{-1}, pod length and seed pod^{-1} of soybean

Interaction b/w LN	Chlorophyll index (SPAD)	Dry matter (g)	Nodules plant^{-1}	Pods length (cm)	Seeds pod^{-1}
L_1N_1	21.27	45.07	10.34	34.38	2.97
L_1N_2	26.46	51.67	20.15	43.93	3.80
L_1N_3	28.13	57.40	22.71	45.89	4.03
L_1N_4	33.59	66.37	28.22	53.82	4.60
L_1N_5	24.03	49.42	15.37	39.22	3.50
L_1N_6	27.14	55.24	21.24	43.97	3.83
L_1N_7	31.40	63.26	25.92	51.89	4.24
L_1N_8	33.78	69.50	30.11	55.89	4.63
L_2N_1	22.13	47.47	13.23	37.89	3.23
L_2N_2	32.19	64.94	27.41	51.93	4.48
L_2N_3	30.78	62.40	23.14	46.90	4.13
L_2N_4	39.12	75.36	33.51	59.79	5.03
L_2N_5	24.34	51.43	19.44	39.14	3.37
L_2N_6	31.14	62.31	24.37	49.87	4.17
L_2N_7	36.03	71.38	30.57	57.86	4.90
L_2N_8	41.25	81.33	39.43	63.80	5.40
SE(d)±	0.64	0.86	3.36	0.310	0.180
CD ($p < 0.05$)	1.32	1.765	7.11	0.64	0.369

the treatment including N_8, followed by N_7 (67.32 g) and N_4 (71.87 g). The control treatment (N_1) showed the lowest dry matter (46.26 g), suggesting the necessity for nutrition in addition to enhance biomass production. The interaction was significant (CD = 1.765), indicating the enhanced dry matter accumulation with ridge and furrow cultivation along with balanced fertilization. Increased plant height and dry matter production adopting the BBF and ridges and furrow methods in comparison to the flat bed method (19, 20).

Number of nodules plant^{-1}

The ridge and furrow method, with 23.671 nodules plant^{-1}, was significantly better compared to the flatbed system, which has 19.413 nodules plant^{-1}. The improved aeration and root-zone conditions under ridge and furrow possibly facilitated superior nodule development and nitrogen fixation. The highest nodule count (26.43) was noted in the N_4 treatment. The control treatment had the lowest nodule count (15.81), demonstrating the crucial effect of nutrition availability on biological nitrogen fixing. The interaction between both was statistically significant, indicating that ridge and furrow with adequate nitrogen-phosphorus fertilization enhances nodule formation, similar result also found in Moong bean (21).

Effect of land configuration and nutrient management on yield attributes

Number of pods plant^{-1}

The ridge and furrow method resulted in significantly more pods (50.89) when compared to the flat bed method (46.12). This can be attributed to enhanced growth of root systems, nutrient absorption and higher plant vigor in the ridge and furrow system. The nutrient treatment including N_8 produced the highest pods (59.84), followed by N_4 (56.81) and N_7 (54.88). The control group had the lowest number of pods (36.13), indicating the effect of nutrient inadequate supply on reproductive growth. The interaction effect was significant (CD = 0.64), showing the necessity of combining ridge and furrow methods with proper nutrient management to maximize pod development. These findings are in accordance with the previous studies (22, 23) experimental results in which they reported that the ideal methods of cultivation and land configuration were broad bed furrow and ridge and furrow in soybean. The results align with the findings of former research (24) in which similarly reported significant enhancements in yield attributes such as the number of pods plant^{-1}, pod length, number of seeds pod^{-1}, biological yield, harvest index and oil yield with increased phosphorus levels and recommended dose of fertilizers compared to the control group. Balanced nutrient availability during flowering supports flower retention and pod formation.

Pod length (cm)

Pod length was significantly higher in ridge and furrow (4.34 cm) than in flatbed (3.95 cm). The increased pod length in ridge and furrow systems might be attributed to improved absorption of nutrients and assimilates to reproductive organs. The longest pods (5.02 cm) were observed in treatment with N_8, followed by N_4 (4.82 cm) and N_7 (4.57 cm). The control showed the shortest pods at 3.1 cm, indicating that pod development is significantly influenced by nutrition availability. The interaction effect was significant, indicating that ridge and furrow method with optimum fertilization improve pod elongation. Enhanced pod elongation under N8 could be attributed to optimal assimilate supply during reproductive development. This result is in support with the findings in green gram (25).

Number of seeds pod^{-1}

The ridge and furrow method (2.71 seeds pod^{-1}) showed a significantly higher seed number than the flat bed (2.48 seeds pod^{-1}). The increased seed number in ridge and furrow systems may result from increased reproductive efficiency and assimilation allocation. The nutrient treatment comprising N_8 yielded the highest seed number pod^{-1} (3.2), followed by N_4 (2.95) and N_7 (2.86). The minimum seed number (1.85) was recorded in the control, highlighting the significance of nutrition availability in seed formation and growth. The interaction between land configuration and nutrient management was statistically significant (CD = 0.154, $p < 0.05$), suggesting that ridge and furrow cultivation, combined with balanced fertilization, enhances seed production. Higher levels of phosphorus fertilizer combined with nitrogen and farmyard manure may be attributed to its effect on root system development, enhanced seed number and size and improved fruit setting (26). Increased seed number under N_8 and L_2 treatments reflects improved source-sink balance and nutrient remobilization efficiency.

Test weight (g)

The ridge and furrow method showed a significantly higher test weight (12.16 g) compared to the flat bed system (11.32 g) as represented in Table 5. The increased test weight under ridge and furrow can be ascribed to improved soil aeration and nutrient absorption, leading to improved grain filling. The greatest test weight (13.47 g) among nutrient treatments was observed in the combination of N_8, followed by N_4 (12.96 g) and N_7 (12.62 g). The minimum test weight (9.82 g) was recorded in the control, highlighting the importance of proper supply of nutrients for grain development. The interaction was significant (CD = 0.47,), suggesting that the ridge and furrow system with balanced supply of nutrients enhances seed weight as shown in Table 6. Adequate N and P supply ensures better assimilate translocation during grain filling, thereby enhancing seed weight. Similar findings have been reported in French bean (27).

Seed yield (kg ha^{-1})

The seed yield was significantly higher in ridge and furrow (2181.69 kg ha^{-1}) than in flatbed methods (1994.75 kg ha^{-1}). The increasing seed yield in ridge and furrow systems can be attributed to better nutrient absorption, increased moisture accessibility and optimized root growth, resulting in increased biomass production and grain filling. The maximum seed yield

Table 5. Effect of land configuration and nutrient management on test weight, harvest index, seed yield, stover yield and protein content of soybean

Treatments	Test weight (g)	Harvest index (%)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Protein content (%)
Land configuration					
L_1- Flat bed	11.32	35.26	1994.75	3654.17	38.06
L_2- Ridge & Furrow	12.16	35.50	2181.69	3926.19	38.86
SE(d)	0.081	0.152	12.60	17.181	0.144
CD	0.166	NS	25.86	35.26	0.289
Nutrient management					
N_1- Control	9.82	33.81	1664.93	3134.55	35.98
N_2- 25 % N +100 % P	11.46	35.26	2073.72	3806.12	38.31
N_3- 50 % NP	11.60	35.17	2037.77	3670.58	38.12
N_4- 75 % N + 100 % P	12.96	35.88	2376.48	4242.83	40.02
N_5- Only FYM	10.48	35.86	1816.22	3249.83	37.25
N_6- 25 % N + 25 % P + 75 % FYM	11.50	34.95	2014.47	3752.35	38.31
N_7- 50 % N + 50 % P + 50 % FYM	12.62	35.23	2262.53	4162.35	39.61
N_8- 75 % N + 25 % FYM + 75 % P	13.47	36.36	2459.63	4302.85	40.0
SE(d)±	0.161	0.604	25.212	34.36	0.29
CD ($p < 0.05$)	0.331	0.62	51.73	70.52	0.59

Table 6. Interaction between land configuration and nutrient management on test weight, harvest index, seed yield, stover yield and protein content of soybean

Interaction b/w LN	Test weight (g)	Harvest index (%)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Protein content (%)
L_1N_1	9.50	33.48	1558.3	3093.63	35.37
L_1N_2	10.90	35.09	1928.4	3568.50	37.43
L_1N_3	11.47	35.35	2027.3	3708.13	38.10
L_1N_4	12.50	35.54	2261.3	4100.80	39.54
L_1N_5	10.40	35.94	1741.7	3104.13	37.27
L_1N_6	11.00	35.02	1940.7	3600.73	38.07
L_1N_7	12.07	35.64	2160.7	3901.83	39.12
L_1N_8	12.70	36.02	2339.6	4155.60	39.60
L_2N_1	10.13	34.15	1771.6	3175.47	36.60
L_2N_2	12.02	35.43	2219.0	4043.73	39.20
L_2N_3	11.73	36.05	2048.2	3633.03	38.13
L_2N_4	13.43	36.23	2491.7	4384.87	40.47
L_2N_5	10.57	35.77	1890.7	3395.53	37.23
L_2N_6	12.00	34.85	2088.3	3903.97	38.55
L_2N_7	13.17	34.84	2364.4	4422.87	40.10
L_2N_8	14.23	36.70	2579.7	4450.10	40.60
SE(d)±	0.23	0.43	35.65	48.59	0.41
CD ($p < 0.05$)	0.47	NS	73.17	99.72	NS

(2459.63 kg ha^{-1}) across nutrient treatments was recorded in N_8, followed by N_4 (2376.48 kg ha^{-1}) and N_7 (2262.53 kg ha^{-1}). The minimum yield (1664.93 kg ha^{-1}) was recorded in the control group (N_1), indicating the essential need of nutrient management in optimizing production. The interaction effect between land configuration and nutrient management was significant, indicating that the combination of ridge and furrow with adequate fertilizer administration significantly improves seed yield. This result is in support with the findings of previous study (28) in Soybean + Pigeon pea intercropping. The N_8 + L_2 treatment achieved the highest seed yield due to its synergistic effects on vegetative vigor, reproductive success and efficient resource utilization.

Stover yield (kg ha^{-1})

Stover yield was significantly affected by land configuration, with ridge and furrow (3926.19 kg ha^{-1}) resulting in more stover yield than flatbed (3654.17 kg ha^{-1}). The increased stover yield in ridge and furrow systems could result from improved vegetative growth, superior nutrient availability and improved water utilization. The maximum stover yield (4302.85 kg ha^{-1}) was observed under N_8, followed by N_4 (4242.83 kg ha^{-1}) and N_7 (4162.35 kg ha^{-1}). The lowest stover yield (3134.55 kg ha^{-1}) was recorded in the control (N_1), highlighting the need for adequate fertilizer supply in enhancing vegetative biomass. The interaction was significant (CD = 99.72), confirming that ridge and furrow, when combined with balanced fertilization, enhances stover yield. Improved biomass production under N_8 and ridge-furrow treatment supports not only grain yield but also fodder availability and soil carbon recycling. Similar results have also been reported in study (29) which resulted in biological yield of soybean increased significantly with increasing levels of phosphorus fertilization.

Harvest index (%)

The harvest index showed no significant variation between ridge and furrow (35.50 %) and flatbed (35.26 %), indicating that land configuration alone may not directly influence the ratio of economic yield to biological output. The highest harvest index (36.36 %) among nutritional treatments was observed in N_8, followed by N_4 (35.88 %). The control had the lowest harvest index at 33.81 %, indicating that a balanced nutrient supply improves biomass allocation towards seed output. The interaction effect was non-significant (NS), suggesting that the harvest index remained similar across treatments. The higher harvest index values were associated with reduced phosphorus application rates (30). The harvest index is determined by the distribution of photosynthates between harvesting and non-harvesting organs throughout the crop growth phase (31). The variation in harvest index may result from differences in the allocation of photosynthates between seed and vegetative components under various phosphorus fertilization treatments. Stable harvest index across treatments suggests proportionate biomass partitioning even under enhanced input regimes.

Protein content (%)

The protein content was higher in the ridge and furrow method (38.86 %) than in the flatbed system (38.06 %). The ridge and furrow technique improves soil aeration, root development and nutrient availability, hence facilitating increased nitrogen absorption and protein synthesis. Nutrient management significantly influenced protein content, with the highest levels recorded under N_4 (40.02 %), followed by N_8 (40.00 %). The significant increase in protein content from these treatments can be attributed to the availability of nitrogen, which is an essential component of amino acids and proteins and the synergistic role of phosphorus in promoting protein synthesis. In contrast, the control had the lowest protein content at 35.98 %, highlighting the critical importance of nitrogen and phosphorus supplementation in enhancing seed quality (32). The increase in protein content under higher N and P availability confirms their roles in amino acid synthesis and seed quality. However, yield-protein dilution effect was minimal.

Correlation Scatter plot matrix of growth parameters

A scatter plot matrix was created to analyze the correlations among important plant growth metrics, such as plant height, leaf area, branch count, leaf count, chlorophyll index, stem girth, dry matter and nodules plant^{-1}. The off-diagonal scatter plots indicate pairwise correlations among these variables, showing a distinct pattern of positive interactions, especially between plant height and leaf area, stem girth and dry matter, as well as chlorophyll index and leaf number. The diagonal histograms depict the distribution of each variable, highlighting variations in data dispersion. The data indicates that leaf area and stem girth are significant indicators of overall plant growth and output Fig. 3 facilitates interpretation of the relationships between morphological and physiological variables, providing knowledge about plant performance across various treatments. Strong correlations between stem girth, dry matter and leaf area underline their importance as predictors of productivity.

Correlation Scatter plot matrix of yield parameters

The scatter plot matrix indicated in Fig. 4 illustrates the correlations among yield-contributing characteristics and yield in a crop study, including pod length, test weight, stover yield, seed yield, protein content and harvest index. The off-diagonal scatter plots depict pairwise correlations, showing strong positive trends between seed yield and test weight, as well as between stover yield and harvest index. The diagonal histograms illustrate the distribution for specific attributes, revealing different types of data dispersion. The findings indicate that characteristics such as test weight and pod length significantly affect overall yield.

Principal component analysis (PCA)

The PCA biplot (Fig. 5) depicts the interactions among key plant growth measures, revealing strong positive relationships among nodules plant^{-1}, plant height, dry matter, chlorophyll index, leaves, leaf area and branches. These variables strongly influence PC1, highlighting the importance they play in explaining plant growth variability. This PCA biplot indicated in Fig. 6 demonstrates the correlations among essential yield-related features in the dataset. The harvest index is prominently shown along the primary component axis, signifying its substantial role in production variability. Characteristics such as seeds per pod, seed weight, pod length, seed yield and pods per plant are closely associated, indicating a positive association among them. The overall yield is described independently, signifying a distinct level of impact on key components. The distribution of data points signifies changes in treatment or genotype, facilitating the identification of primary factors influencing yield performance. PCA confirmed that nodulation, chlorophyll index and dry matter are principal contributors to growth variability, while pod length and test weight dominate yield dimensions. These traits can guide future selection or agronomic interventions.

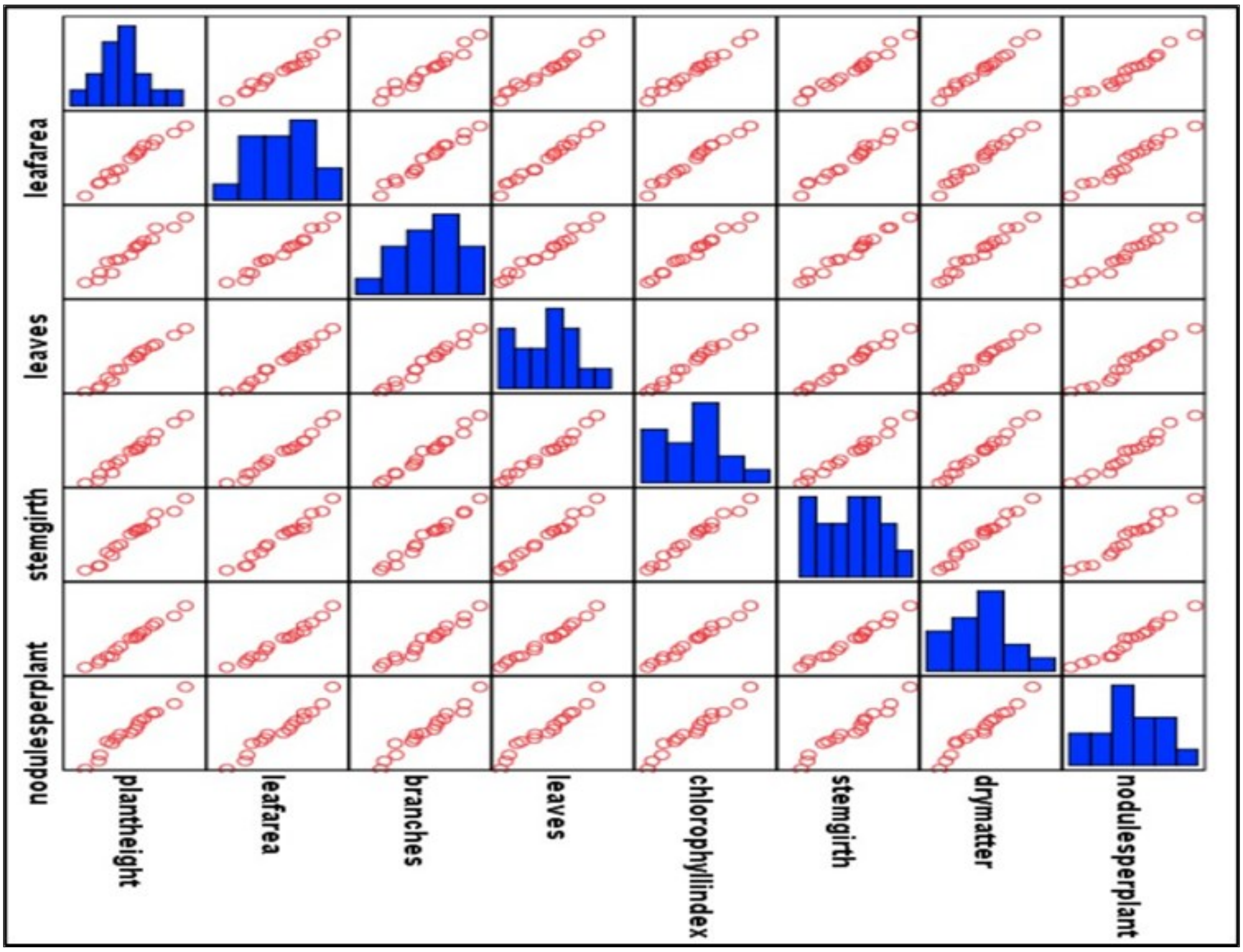

Fig. 3. Correlation scatter plot matrix between the growth parameters of soybean.

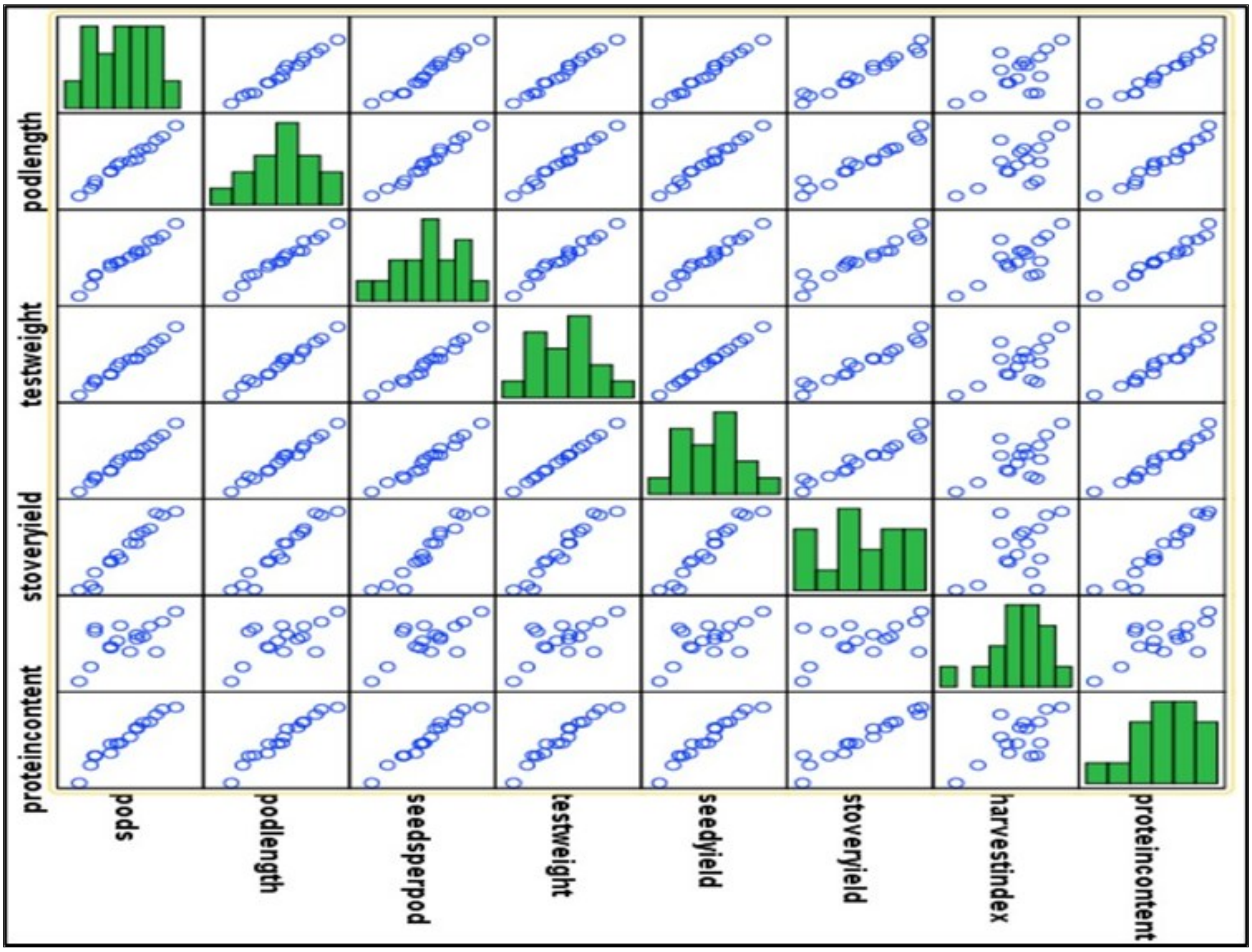

Fig. 4. Correlation scatter plot matrix between the yield and yield attributes of soybean.

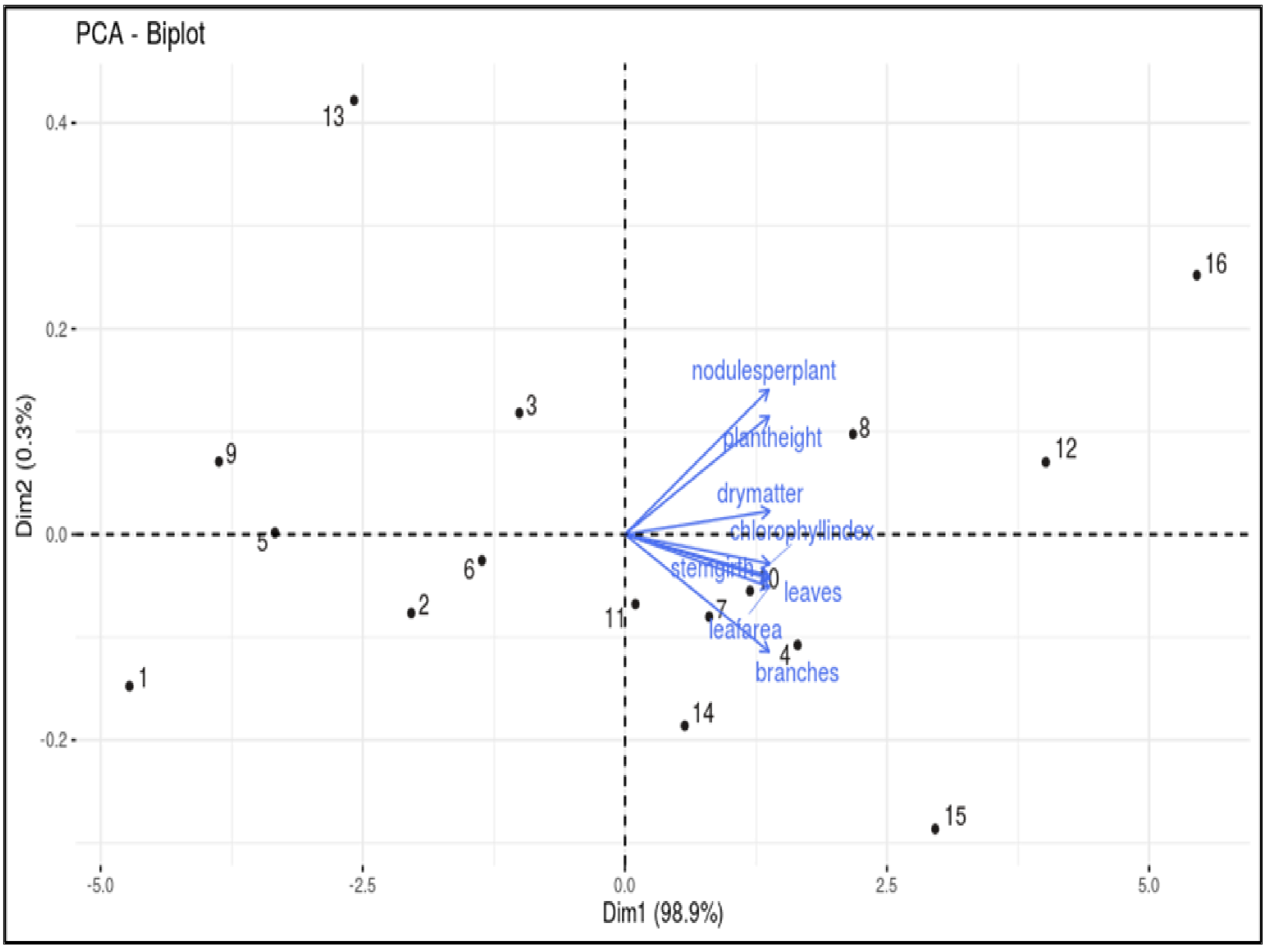

Fig. 5. Principal component analysis biplot of growth parameters of soybean.

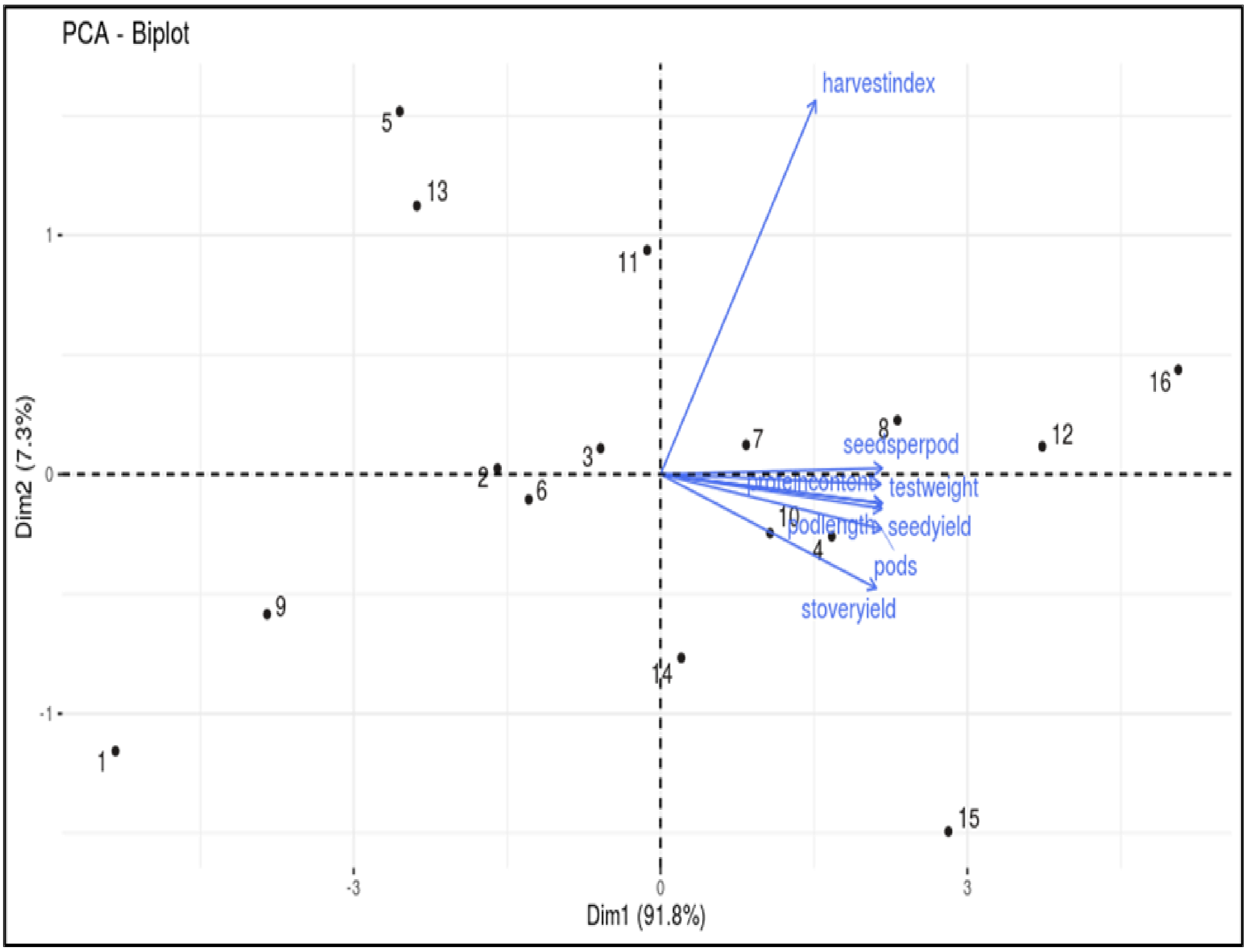

Fig. 6. Principal component analysis biplot of yield and quality parameters of soybean.

Conclusion

The ridge and furrow method performed better than the flatbed system, resulting in higher plant height, leaf area, branches, leaves, stem girth, chlorophyll index, dry matter accumulation, pods per plant and seed yield. The nutrient management treatment containing 75 % nitrogen, 25 % farmyard manure and 75 % phosphorus demonstrated the most beneficial results for plant growth parameters, yield and quality traits, including seed yield (2459.63 kg ha^{-1}), stover yield (4302.85 kg ha^{-1}) and protein content (40.00 %). The combination of organic (FYM) and inorganic (N and P) fertilizers synergistically enhanced nutrient availability, improved physiological efficiency and increased biomass output. The control treatment repeatedly exhibited the lowest results, highlighting the significance of balanced fertilization. The interaction between land configuration and nutrient management was statistically significant for most measures, suggesting that the ridge and furrow system, when combined with optimal nutrient supply, enhances growth, yield and quality. The data indicates that adopting a ridge and furrow planting method with 75 % nitrogen, 25 % farmyard manure and 75 % phosphorus is an effective approach to enhance crop yield and seed quality in sustainable agricultural systems. Future research should focus on validating these findings across seasons and soil types and assessing long-term effects on soil health.

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Authors' contributions

AC and ZAS did work in the field. P, K and LM wrote the paper; AS and SS did the analysis and ST did the corrections. 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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