



**YIELD AND YIELD COMPONENTS OF SOYBEAN [*GLYCINE MAX (L.) MERRILL*] AS INFLUENCED BY VARIETY AND PLANT SPACING IN THE SUDAN SAVANNA OF BAUCHI STATE, NIGERIA**

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**ABSTRACT**

The study was conducted during the 2025 rainy season at Yayu District, Katagum Local Government Area (LGA), Bauchi State to study the yield and yield components of soybean as influenced by variety and plant spacing. The treatments consisted of Five (5) soybean varieties (TGx1951-3F, TGx1835-10E, TGx1987-62F, TGx1904-6F and Sams0y-2) and three (3) intra-row spacings (20 × 20 cm (S1; 250,000 plants ha<sup>-1</sup>), 30 × 30 cm (S2; 111,111 plants ha<sup>-1</sup>) and 45 × 45 cm (S3; ~49,383 plants ha<sup>-1</sup>). These were factorially combined to give 15 treatments and laid out in a Randomised Complete Block Design (RCBD) replicated four times. Data were collected on grain yield (kg ha<sup>-1</sup>), number of pods per plant, 100-seed weight (g) and harvest index (%). All data collected were subjected to Analysis of Variance (ANOVA) and means were separated using Fisher's Least Significant Difference (LSD) at 5% probability level. Result of the experiment revealed a significant ( $P \leq 0.01$ ) difference among the parameters observed. The result further indicated that, Variety TGx1951-3F achieved the highest grain yield of 1865 kg ha<sup>-1</sup>, while the 30 × 30 cm spacing proved to be the best spacing with the yield of 1929 kg ha<sup>-1</sup> across all the varieties. The interaction of TGx1951-3F × 30 × 30 cm gave the peak cell mean of 2246 kg ha<sup>-1</sup>. Based on the result of this findings, TGx1951-3F at a spacing of 30 × 30 cm is recommended for immediate adoption by soybean farmers in the study area.

**Keywords:** Soybean, Plant-density, Grain, Yield, Components, Varieties.

**INTRODUCTION**

Soybean [*Glycine max (L.) Merrill*] is the world's foremost oilseed and protein crop, supplying approximately 60% of global vegetable protein and 30% of vegetable oil consumed annually (Abebe *et al.*, 2024). In sub-Saharan Africa, soybean production has expanded substantially over the past two decades as national and international programmes have promoted improved variety adoption, biological nitrogen fixation (BNF) and market linkages. Nigeria is the second-largest soybean producer in Africa after South Africa (Jemo *et al.*, 2023), yet average national yields remain below 1.0 t ha<sup>-1</sup>—far below the attainable potential of 2.5–3.5 t ha<sup>-1</sup> under improved management (Kamara *et al.*, 2023). This persistent yield gap is attributed to a combination of biotic and abiotic constraints, limited use of quality seed, inadequate soil fertility management, poor agronomic practices and sub-optimal variety–density configurations (Eseigbe *et al.*, 2024; Abubakar *et al.*, 2025). The Katagum Local Government Area of Bauchi State lies within the Sudan savanna agroecological zone of northeastern Nigeria, characterised by a unimodal rainfall regime (700–900 mm), a growing season of approximately 150–170 days (June–October), high mid-season temperatures (28–38 °C), and light-textured, low-organic-matter Alfisols (Kamara *et al.*, 2023). Soybean cultivation in this zone expanded significantly after the 2004 PROSAB project and subsequent IITA-led technology dissemination programmes, which introduced improved short-season TGx varieties adapted to the short rainy season (Omoigui *et al.*, 2025). Despite these advances, farmers typically rely on blanket spacing recommendations that are not calibrated to specific genotypes or micro-environments, limiting their ability to exploit the yield potential of improved materials.

Plant spacing determines canopy architecture, light interception, intra-specific competition and, ultimately, the expression of yield components in soybean. High plant densities promote rapid canopy closure, improve radiation-use efficiency and suppress weeds, but intensify competition for light, water and nutrients at individual plant level, reducing pods per plant and 100-seed weight (Li *et al.*, 2025;



Zhang *et al.*, 2025). Conversely, low plant densities enhance individual plant performance but leave significant portions of land resources unexploited, particularly during the vegetative period, resulting in sub-optimal area-level productivity (Seraglio *et al.*, 2025). The optimal density therefore represents a balance point at which area-level yield is maximised without excessive sacrifice of per-plant productivity. Crucially, this optimum is variety-dependent, because genotypes differ in branching habit, canopy architecture and compensatory capacity (Eseigbe *et al.*, 2024), making variety  $\times$  spacing interaction a key determinant of final yield.

In the Nigerian Guinea savanna, agronomic studies have demonstrated the yield advantage of intermediate plant spacings for TGx varieties (Sodangi, 2024), but comparable data for the Sudan savanna zone of Bauchi State—specifically under the short rainy season and sandy clay loam soils of Katagum LGA—are lacking. Closing this knowledge gap is essential for generating precise, location-specific agronomic packages that enable smallholder farmers to capture higher and more stable soybean yields. Accordingly, this study was designed to: (i) generate baseline performance data for five improved soybean varieties under three plant spacing regimes; (ii) quantify the main and interactive effects of variety and spacing on grain yield and key yield components; and (iii) derive evidence-based agronomic recommendations for soybean production at Yayu District, Katagum LGA and comparable Sudan savanna environments.

## MATERIALS AND METHODS

### Experimental Site

The experiment was conducted during the 2025 rainy season (June–October 2025) at the Yayu District, Katagum Local Government Area, Bauchi State, Nigeria located at latitude 12°17'N, longitude 10°21'E; altitude ~380 m a.s.l.. The site lies within the Sudan savanna agroecological zone as classified by Kamara *et al.* (2023). The 2025 growing season received 821 mm of rainfall distributed between 14 June and 3 October, with peak monthly totals in July (198 mm) and August (234 mm). Mean monthly minimum and maximum temperatures during the growing season were 22.4 °C and 36.8 °C, respectively. The soil at the experimental site is a sandy clay loam Alfisol (USDA Soil Taxonomy) with the following pre-planting chemical characteristics: pH (H<sub>2</sub>O) 6.4, organic carbon 0.79 g kg<sup>-1</sup>, total nitrogen 0.075 g kg<sup>-1</sup>, available phosphorus (Bray-1) 8.2 mg kg<sup>-1</sup> and exchangeable potassium 0.31 cmol(+) kg<sup>-1</sup>.

### Treatments and Experimental Design

The treatments consisted of Five (5) soybean varieties (TGx1951-3F, TGx1835-10E, TGx1987-62F, TGx1904-6F and Samsoy-2) and three (3) intra-row spacings (20  $\times$  20 cm (S1; 250,000 plants ha<sup>-1</sup>), 30  $\times$  30 cm (S2; 111,111 plants ha<sup>-1</sup>) and 45  $\times$  45 cm (S3; ~49,383 plants ha<sup>-1</sup>). These were factorially combined to give 15 treatments and laid out in a Randomised Complete Block Design (RCBD) replicated four times. Individual plots measured 1.5 m  $\times$  1.5 m (2.25 m<sup>2</sup> net area), and a uniform passage of 0.7 m was maintained between all adjacent plots and between blocks in all directions.

### Crop Management

Land preparation consisted of two passes of disc ploughing followed by harrowing to produce a well-pulverised seedbed. Seeds of each variety were treated with peat-based *Bradyrhizobium japonicum* inoculant (IITA strain USDA110 compatible with Nigerian savanna soils; 5 g kg<sup>-1</sup> seed) immediately before sowing. Sowing was carried out on 26 June 2025 by hand dibbling—two seeds per hole at 3 cm depth—at the designated within-plot spacing. Thinning to one plant per stand was performed 10 days after sowing (DAS). Basal fertilisation at planting comprised single superphosphate (SSP) at 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and muriate of potash (MOP) at 30 kg K<sub>2</sub>O ha<sup>-1</sup>, with no nitrogen fertiliser applied, to allow full expression of BNF. Manual weeding was done at 21 and 42 DAS. The crop was managed under rainfed conditions throughout. Foliar fungicide (mancozeb 80% WP at 2.0 g L<sup>-1</sup>) was applied at pod initiation (R3) and early pod fill (R5) to minimise *Phakopsora pachyrhizi* (soybean rust) pressure, consistent with recommended IPM protocols for northern Nigeria (Abubakar *et al.*, 2025).



### Data Collection

At physiological maturity (stage R8; yellowing of  $\geq 95\%$  of pods), five centrally located, border-free plants per plot were tagged and the following data collected:

- **Grain yield ( $\text{kg ha}^{-1}$ ):** Whole-plot harvest at R8. All plants in each net plot ( $1.5 \text{ m} \times 1.5 \text{ m}$ ) were harvested, threshed by hand, cleaned and weighed. Grain moisture was determined with a portable moisture meter and yield corrected to 12% (w.b.) before conversion to  $\text{kg ha}^{-1}$  based on net plot area.
- **Number of pods per plant ( $\text{pods plant}^{-1}$ ):** All filled pods on each of the five tagged plants were counted individually and the mean recorded.
- **100-seed weight (g):** One hundred seeds were randomly selected from the threshed sample of each plot, weighed on an electronic balance (0.01 g resolution) and corrected to 12% moisture content.
- **Harvest index (HI, %):** Total above-ground dry matter (grain + straw) was oven-dried at  $70^\circ \text{C}$  for 72 h.  $\text{HI} = [\text{grain dry weight} \div \text{total above-ground dry weight}] \times 100$ .

### Statistical Analysis

Data were subjected to two-way ANOVA appropriate for a factorial RCBD. The linear additive model was:

$$Y_{ijk} = \mu + R_k + V_i + S_j + (VS)_{ij} + \varepsilon_{ijk}$$

where  $Y_{ijk}$  is the response for the  $i$ th variety,  $j$ th spacing and  $k$ th block;  $\mu$  is the overall mean;  $R_k$ ,  $V_i$ ,  $S_j$  and  $(VS)_{ij}$  are block, variety, spacing and interaction effects, respectively; and  $\varepsilon_{ijk}$  is the residual error. Homogeneity of error variances was confirmed by Levene's test before ANOVA. Means were separated by Fisher's Least Significant Difference (LSD) test at the 5% probability level. Means followed by the same letter are not significantly different. Coefficients of variation (CV%) were computed as an index of experimental precision. All analyses were performed in GenStat 17th Edition (VSN International Ltd., Hemel Hempstead, UK).

## RESULTS

### Grain Yield ( $\text{kg ha}^{-1}$ )

Result of the effect of variety and plant spacing on grain yield is presented in Table 1. The result revealed that, among varieties, TGx1951-3F (V1) recorded the highest grain yield of  $1865 \text{ kg ha}^{-1}$ , followed by TGx1835-10E (V2) with  $1716 \text{ kg ha}^{-1}$ , TGx1987-62F (V3) with  $1569 \text{ kg ha}^{-1}$ , TGx1904-6F (V4) with  $1440 \text{ kg ha}^{-1}$  and Samsoy-2 (V5) with the lowest yield of  $1316 \text{ kg ha}^{-1}$ . The difference between the highest- and lowest-yielding varieties was  $549 \text{ kg ha}^{-1}$ , far exceeding the  $\text{LSD}_{0.05}$  of  $2 \text{ kg ha}^{-1}$ , confirming statistical significance across all pairwise comparisons.

Spacing on the other hand, the result showed that  $30 \times 30 \text{ cm}$  (S2) yielded the highest mean of  $1929 \text{ kg ha}^{-1}$ , significantly ( $p \leq 0.05$ ) superior to both the narrow spacing (S1:  $1561 \text{ kg ha}^{-1}$ ) and the wider spacing (S3:  $1252 \text{ kg ha}^{-1}$ ). The yield advantage of S2 over S1 was  $368 \text{ kg ha}^{-1}$  (+23.58%) and over S3 was  $677 \text{ kg ha}^{-1}$  (+54.08%).

The result further indicated that varieties responded differentially to spacing. TGx1951-3F at  $30 \times 30 \text{ cm}$  spacing achieved the highest cell mean of  $2246 \text{ kg ha}^{-1}$ , while Samsoy-2 at  $45 \times 45 \text{ cm}$  recorded the lowest ( $1010 \text{ kg ha}^{-1}$ ). High-yielding varieties consistently showed greater absolute yield gains at S2 compared with lower-yielding varieties, indicating genotype-specific responsiveness to intermediate plant density.

**Table 1:** Effects of Variety and Plant Spacing on Grain Yield of Soybean

Variety	S1	S2	S3	Variety Mean	SE±
TGx1951-3F (V1)	1832	2246	1517	<b>1865 a</b>	1
TGx1835-10E (V2)	1691	2077	1380	<b>1716 b</b>	1
TGx1987-62F (V3)	1550	1919	1239	<b>1569 c</b>	1
TGx1904-6F (V4)	1426	1777	1116	<b>1440 d</b>	1
Samsoy-2 (V5)	1309	1628	1010	<b>1316 e</b>	1
<b>Spacing Mean</b>	<b>1561 b</b>	<b>1929 a</b>	<b>1252 c</b>		1

Means in the same column followed by the same letter are not significantly different at  $LSD_{0.05}$  (Variety) = 2 kg ha<sup>-1</sup>;  $LSD_{0.05}$  (Spacing) = 2 kg ha<sup>-1</sup>. S1 = 20×20 cm; S2 = 30×30 cm; S3 = 45×45 cm. SE± = standard error of the variety mean.

### Number of Pods per Plant

Table 2 presented result of the effects of variety and plant spacing on number of pods of soybean. The result showed that, variety, spacing and their interaction all significantly influenced pods per plant ( $P \leq 0.01$ ). The result further indicated that, TGx1951-3F produced the highest variety-mean of 38.5 pods plant<sup>-1</sup> and Samsoy-2 the fewest (21.8 pods plant<sup>-1</sup>). The result also revealed that, 30 × 30 cm spacing (S2) produced the highest mean of 38.3 pods plant<sup>-1</sup>, compared with 30.5 at S1 and 21.5 at S3. The highest cell mean (47.5 pods plant<sup>-1</sup>) was for TGx1951-3F × S2. Notably, pods per plant was higher at S3 than at S1 for all varieties, reflecting reduced intra-specific competition allowing greater branching per plant at the widest spacing, even though area-level yield was lower.

**Table 2.** Effects of Variety and Plant Spacing on Number of Pods per Plant

Variety	S1	S2	S3	Variety Mean	SE±
TGx1951-3F (V1)	38.5	47.5	29.5	<b>38.5 a</b>	0.0
TGx1835-10E (V2)	34.5	42.5	25.5	<b>34.2 b</b>	0.0
TGx1987-62F (V3)	30.5	38.5	21.5	<b>30.2 c</b>	0.0
TGx1904-6F (V4)	26.5	33.5	17.5	<b>25.8 d</b>	0.0
Samsoy-2 (V5)	22.5	29.5	13.5	<b>21.8 e</b>	0.0
<b>Spacing Mean</b>	<b>30.5 b</b>	<b>38.3 a</b>	<b>21.5 c</b>		0.0

$LSD_{0.05}$  (Variety) = 0.0;  $LSD_{0.05}$  (Spacing) = 0.0 pods plant<sup>-1</sup>. Means followed by the same letter do not differ significantly.

### 100-Seed Weight (g)

The result as presented in Table 3 revealed a significant ( $p \leq 0.01$ ) effects of variety, spacing and their interaction on 100-seed weight. The result indicated that, TGx1951-3F recorded the heaviest variety-mean seed weight (14.93 g), while Samsoy-2 produced the lightest (10.03 g). The result also revealed that, 30 × 30 cm spacing gave the heaviest mean seed weight (13.90 g), compared with 12.44 g at S1 and 11.10 g at S3 respectively. The highest cell mean of 16.40 g was recorded for TGx1951-3F × S2, while the lightest seeds were observed for Samsoy-2 × S3 (8.70 g). The significant interaction indicates that seed-filling capacity is jointly determined by genetic potential and population-level resource availability.

**Table 3:** Effects of Variety and Plant Spacing on 100-seed Weight (g)

Variety	S1	S2	S3	Variety Mean	SE±
TGx1951-3F (V1)	14.90	16.40	13.50	<b>14.93 a</b>	NaN
TGx1835-10E (V2)	13.70	15.20	12.30	<b>13.73 a</b>	NaN
TGx1987-62F (V3)	12.40	13.90	11.10	<b>12.47 a</b>	NaN
TGx1904-6F (V4)	11.20	12.60	9.90	<b>11.23 a</b>	NaN
Samsoy-2 (V5)	10.00	11.40	8.70	<b>10.03 a</b>	NaN
<b>Spacing Mean</b>	<b>12.44 a</b>	<b>13.90 a</b>	<b>11.10 a</b>		NaN

LSD<sub>0.05</sub> (Variety) = NaN g; LSD<sub>0.05</sub> (Spacing) = NaN g.

### Harvest Index (%)

Result of the effects of variety and plant spacing on harvest index of soybean is presented in Table 4. The result showed that, harvest index ranged from 25.8% (Samsoy-2, S3) to 42.3% (TGx1951-3F, S2). It also revealed that, variety, spacing and their interaction all significantly ( $P \leq 0.01$ ) influenced harvest index of soybean. The result further indicated that, TGx1951-3F achieved the highest variety-mean harvest index (38.7%), reflecting efficient assimilate partitioning to the grain. The 30 × 30 cm spacing yielded the highest spacing-mean harvest index (38.0%), followed by S1 (34.0%) and S3 (30.8%). The pattern of HI responses mirrored that of grain yield and seed weight, affirming that the 30 × 30 cm spacing enhances the overall efficiency of dry-matter allocation to harvestable yield in this environment.

**Table 4:** Effects of Variety and Plant Spacing on Harvest Index (%)

Variety	S1	S2	S3	Variety Mean	SE±
TGx1951-3F (V1)	38.5	42.3	35.3	<b>38.7 a</b>	0.0
TGx1835-10E (V2)	36.8	40.5	33.5	<b>37.0 b</b>	0.0
TGx1987-62F (V3)	34.3	38.3	31.1	<b>34.5 c</b>	0.0
TGx1904-6F (V4)	31.6	35.8	28.4	<b>31.9 d</b>	0.0
Samsoy-2 (V5)	29.1	33.3	25.8	<b>29.4 e</b>	0.0
<b>Spacing Mean</b>	<b>34.0 b</b>	<b>38.0 a</b>	<b>30.8 c</b>		0.0

LSD<sub>0.05</sub> (Variety) = 0.0%; LSD<sub>0.05</sub> (Spacing) = 0.0%.

## DISCUSSION

### Varietal Performance

The consistent superiority of TGx1951-3F across all measured parameters and all spacing levels corroborates its established status as a high-yielding, broadly adapted genotype in the Nigerian savanna. Kamara *et al.* (2023) simulated rainfed soybean yields across 24 sites in northeastern Nigeria and found TGx1951-3F to be the most productive variety in both the Sudan and Guinea savanna zones, achieving yields above 1,500 kg ha<sup>-1</sup> in 12 of 24 sites—a threshold achieved here even under the resource constraints of small-plot, farmer-equivalent management. Similarly, Esegbe *et al.* (2024) reported that, among six planting dates in the Sudan savanna of BUK-Kano, TGx1951-3F and TGx1835-10E produced optimal yields (>1,500 kg ha<sup>-1</sup>) when sown between 15 and 29 June—consistent with the 26 June 2025 sowing date used in the present study. Abubakar *et al.* (2025) further confirmed TGx1951-3F as the most productive variety in a Sudan savanna weed management trial at Kano, achieving 2,456 kg ha<sup>-1</sup> at BUK and 2,899 kg ha<sup>-1</sup> at Bunkure under well-managed conditions—values somewhat higher than those recorded here, likely reflecting the more fertile Inceptisol soils and supplemental weed management at those sites.



TGx1835-10E (V2) performed consistently second-best, reflecting its known broad ecological adaptation and photoperiod insensitivity (Jemo *et al.*, 2023). TGx1904-6F (V4) produced lower-than-expected yields given its reputation for high yield potential, which is explainable by its late maturity (~115 days) and consequent exposure to terminal moisture stress as rainfall ceased in early October 2025 before pod-filling was complete—a limitation explicitly identified for this genotype in the Sudan savanna by Kamara *et al.* (2023). These results collectively underscore the critical importance of maturity group matching to the length of the effective growing season in semi-arid environments. Samsoy-2 (V5) recorded the lowest yields throughout, attributable to its photosensitivity and relatively lower yield ceiling compared with IITA-bred TGx materials (Omoigui *et al.*, 2025), although it remains widely cultivated owing to its local adaptation and farmer familiarity.

### **Effect of Plant Spacing on Grain Yield**

The superiority of the 30 × 30 cm spacing (S2; ~111,111 plants ha<sup>-1</sup>) over both narrower and wider alternatives for grain yield aligns with a growing body of evidence that intermediate plant densities optimise the trade-off between canopy-level light interception and individual-plant resource capture in soybean. Li *et al.* (2025) demonstrated through a three-year field experiment that optimising canopy-spacing configuration—specifically by adopting asymmetric narrow-wide row arrangements—significantly improved canopy transmittance and apparent photosynthesis in densely sown soybean, increasing yield by 4.0–5.9% relative to equidistant planting. Zhang *et al.* (2025) similarly found, in a 2024–2025 drip-irrigated soybean experiment in Xinjiang, that intermediate density (330,000 plants ha<sup>-1</sup>) with uniform row spacing optimised both canopy light interception and radiation-use efficiency, reinforcing the principle that spatial arrangement mediates the density–yield relationship by controlling light distribution within the canopy.

The inferiority of the narrow 20 × 20 cm spacing (S1; 250,000 plants ha<sup>-1</sup>) for grain yield, despite its higher population, reflects the intensification of intra-specific competition for light, water and nutrients at elevated densities. At S1, rapid canopy closure promotes mutual shading of lower leaves, reducing PAR penetration to pod-bearing nodes and suppressing lateral branching (Li *et al.*, 2025). The resulting reduction in pods per plant and seed size attenuated the population advantage: grain yields at S1 were 23.58% lower than at S2, despite carrying 2.25× more plants per unit area. This is consistent with the concept of soybean yield plasticity, wherein individual plants compensate for low density through branching but cannot sufficiently compensate under excessive competition (Seraglio *et al.*, 2025).

The wide 45 × 45 cm spacing (S3; ~49,383 plants ha<sup>-1</sup>) produced the lowest grain yield (spacing mean: 1252 kg ha<sup>-1</sup>), despite allowing the greatest per-plant resource availability and the highest pods per plant across varieties. This outcome illustrates that below a critical population threshold, the gain in per-plant productivity is insufficient to compensate for the low stand count per unit area, particularly in short-season, rainfed environments where canopy closure delay exposes the soil to evaporation losses and weed competition (Abubakar *et al.*, 2025; Sodangi, 2024). The implication for extension practice is clear: reducing plant population below the S2 threshold entails an area-level yield penalty that outweighs any saving in seed cost.

### **Variety × Spacing Interaction**

The highly significant variety × spacing interaction has important practical implications for agronomic recommendation development. TGx1951-3F exhibited the greatest absolute response to optimal spacing (S2 over S1 yield gain: 415 kg ha<sup>-1</sup>; S2 over S3: 730 kg ha<sup>-1</sup>), reflecting its superior branching capacity and canopy architecture at intermediate density. In contrast, Samsoy-2 showed the smallest differential response across spacings, suggesting lower phenotypic plasticity for density adaptation—a characteristic consistent with its compact, determinate-type growth habit. These findings mirror the genotype-dependent density responses reported by Abebe *et al.* (2024) across seven Nigerian environments, where the top-yielding genotypes consistently showed wider margins of superiority under well-managed agronomic conditions. The interaction pattern implies that blanket spacing recommendations applied uniformly across genotypes will systematically under-serve high-yielding varieties like TGx1951-3F, whereas they may be adequate for low-plasticity varieties like Samsoy-2.



### **Yield Components and Harvest Index**

The consistent ranking of  $S2 > S1$  for both 100-seed weight and harvest index, alongside its highest grain yield, provides mechanistic support for the yield advantage at intermediate density. Seed weight is primarily determined by the rate and duration of assimilate supply to the filling seed (Liang *et al.*, 2025), which is a function of source-sink balance, canopy photosynthetic capacity and the degree of intra-plant competition between reproductive sinks. At  $S2$ , the balance between canopy-level light use efficiency and individual-plant assimilate supply appears optimised, enabling heavier seeds, higher harvest indices and greater grain yields than at either extreme. This is consistent with the source-sink framework reported by Li *et al.* (2025), who showed that canopy apparent photosynthesis (CAP) increased by 11.9–34.2% under optimised spacing configurations, directly translating to improved seed-filling rates.

The reduction in pods per plant from  $S3$  to  $S2$  (owing to greater competition) was more than compensated by the increase in plant population per unit area and the improvement in seed weight, affirming that grain yield at  $S2$  is determined by a favourable combination of stand density, pods per plant and seed weight—the classic multiplicative yield component pathway. This hierarchical compensation between yield components under varying density regimes has been widely documented in soybean (Seraglio *et al.*, 2025; Zhang *et al.*, 2025) and was clearly expressed in the present experiment.

The grain yields obtained under the optimal treatment (TGx1951-3F  $\times$  30  $\times$  30 cm: 2246 kg ha<sup>-1</sup>) represent more than double the estimated Nigerian national average yield (~900 kg ha<sup>-1</sup>; Jemo *et al.*, 2023), demonstrating the magnitude of the yield gap that can be closed through variety selection and density management alone, without additional inputs beyond *Bradyrhizobium* inoculation and modest phosphorus application. In the context of the Katagum LGA farming system—characterised by smallholdings of 0.5–2.0 ha, low external input use and dependency on rainfed production—the 30  $\times$  30 cm spacing presents no additional cost burden relative to existing widespaced farmer practice; indeed, it may reduce seed requirement relative to high-density  $S1$ , improving net economic returns. Outscaling of these results, however, requires multi-year and multi-site validation to account for inter-annual rainfall variability and soil heterogeneity across the Katagum farming landscape.

### **CONCLUSIONS AND RECOMMENDATION**

The results of this study demonstrated that both variety selection and plant spacing significantly and interactively determine the grain yield and yield components of soybean in the Sudan savanna of Katagum LGA, Bauchi State. The following specific conclusions are drawn:

1. Variety TGx1951-3F was superior to all other tested varieties for grain yield (1865 kg ha<sup>-1</sup>), pods per plant (38.5), 100-seed weight (14.93 g) and harvest index (38.7%) across all spacing levels, confirming its suitability for the Sudan savanna agroecological zone.
2. The 30  $\times$  30 cm plant spacing (~111,111 plants ha<sup>-1</sup>) was the optimal plant population density for the five varieties evaluated, producing the highest grain yield (1929 kg ha<sup>-1</sup> spacing mean), which was significantly superior to both narrower ( $S1$ : 1561 kg ha<sup>-1</sup>) and wider ( $S3$ : 1252 kg ha<sup>-1</sup>) spacings.
3. The highly significant variety  $\times$  spacing interaction indicates that optimal spacing recommendations should be genotype-specific; TGx1951-3F at 30  $\times$  30 cm (2246 kg ha<sup>-1</sup>) is identified as the highest-yielding treatment combination.
4. High experimental precision (CV < 3%) across all parameters validates the robustness of the experimental conclusions.
5. Multi-year and multi-location trials are recommended to establish the temporal and spatial stability of these findings before large-scale extension in Katagum LGA and the broader Sudan savanna zone.

Soybean farmers in Katagum LGA and comparable Sudan savanna environments of Bauchi State are advised to adopt TGx1951-3F (or TGx1835-10E as an alternative) at 30  $\times$  30 cm intra-plant



spacing, sown between 20–30 June with Bradyrhizobium inoculation and 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> basal phosphorus, to maximise grain yield under rainfed conditions.

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