GENOTYPIC VARIATION AND YIELD OPTIMIZATION IN BAMBARA GROUNDNUT (*Vigna subterranea* (L.) Verdc.) UNDER VARYING PLANT POPULATION DENSITIES IN THE SUDAN SAVANNAH

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Abstract
Bambara groundnut (*Vigna subterranea* L. Verdc.) is an underutilized African legume valued for its resilience to drought and poor soils, yet the genotypic variation in its response to plant population density remains underexplored. This study investigated the growth and yield performance of three bambara groundnut genotypes (Cream Brown Eye, Cream Black Eye, and Mottled Brown Eye) under three population densities (160 × 20 cm, 160 × 30 cm, and 160 × 40 cm) in the Sudan savannah of Nigeria using a split-plot design. Significant effects of genotype, density, and their interaction were observed for plant height, petiole length, and yield components. Wider spacing enhanced vegetative growth, while intermediate density (8 plants m^{-2}) maximized grain yield (1.85 t ha^{-1}), reflecting a parabolic density–yield relationship. Among genotypes, Mottled Brown Eye exhibited superior shelling efficiency (82.4%) and productivity index, indicating greater assimilate partitioning and competitive balance under moderate population pressure. The differential density responses among genotypes highlight the presence of exploitable genetic variation for density tolerance and yield stability. These findings suggest that moderate plant density optimizes canopy development, photosynthetic efficiency, and yield per unit area under semi-arid conditions, providing a framework for genotype-specific planting density recommendations to enhance bmbara groundnut productivity and sustainability in dryland cropping systems.

Keywords: Bambara groundnut, Genotype × density interaction, Tolerance, Yield plasticity

Introduction
Bambara groundnut (*Vigna subterranea* L. Verdc.) is an indigenous African legume that is gaining recognition for its ability to thrive in areas where many conventional crops fail. It is highly valued for its balanced nutritional profile, rich in carbohydrates, proteins, and essential minerals, as well as its capacity to fix atmospheric nitrogen, which improves soil fertility and supports low-input farming systems (Gerrano *et al.*, 2021; Soumaré *et al.,* 2022). These attributes make bambara groundnut one of the most promising crops for building

resilience and food security in the face of increasing climatic variability across sub-Saharan Africa.

Despite its potential, bambara groundnut remains underutilized and poorly improved compared to other legumes such as cowpea or soybean. Its cultivation is still largely confined to traditional smallholder systems, where yields are often less than 1 t ha^{-1}, far below its genetic potential of 2–3 t ha^{-1} (Tan *et al.*, 2020). This yield gap is partly due to a limited understanding of the crops' agronomic requirements and genotypic responses to management factors such as plant population density. Optimizing plant density is critical because it directly influences light interception, nutrient uptake, canopy development, and, ultimately, yield formation (Godoy *et al.*, 2020; Chimonyo *et al.*, 2020). Previous research on grain legumes suggests that yield responses to plant density typically follow a parabolic pattern, with maximum yield occurring at intermediate population levels (Kamara *et al.*, 2018; Zhu *et al.*, 2021). However, such relationships are strongly genotype-dependent, reflecting differences in plant architecture, resource allocation, and competitive ability (Alhassan *et al.*, 2012; Essel *et al.*, 2024). In bambara groundnut, studies conducted in some Sub-Saharan African countries have reported variable density optima depending on rainfall and soil fertility (Kamara *et al.*, 2018; Gerrano *et al.*, 2021; Ajilogba *et al.*, 2022). These inconsistencies highlight the need to consider both genotype and environment when developing site-specific planting recommendations. Moreover, understanding genotypic variation in density tolerance can inform breeding strategies aimed at developing ideotypes suited to resource-limited and semi-arid environments. The Sudan savannah of northern Nigeria offers a unique context for such an investigation. The region experiences high temperatures, erratic rainfall, and sandy soil conditions that test the physiological adaptability of crops. Yet, bambara groundnut is increasingly cultivated here because of its drought resilience and low management demand. Still, information on optimal plant spacing and genotype × density interactions for local landraces remains scarce.

Therefore, this study was designed to evaluate the growth and yield responses of three bambara groundnut genotypes under varying plant population densities in the Sudan savannah environment. Specifically, it aimed to (1) quantify the effects of plant density on key vegetative and reproductive traits, (2) assess genotypic variation in density tolerance and yield efficiency, and (3) identify an optimal planting density that balances resource-use efficiency with productivity.

Materials and methods

Study Site and Environmental Conditions

The experiment was conducted during the 2023 rainy season at the Teaching and Research Farm of Aliko Dangote University of Science and Technology (ADUSTECH), Gaya, Kano State, Nigeria (11°48′ N, 8°59′ E; 442 m a.s.l.). The site lies within the Sudan savannah agro-ecological zone, characterized by a distinct wet season (June–September) and a dry season (October–May). Mean annual rainfall ranges between

900 and 1100 mm, and average monthly temperatures vary from 22 °C to 35 °C. Daily weather data for the cropping period were obtained from https://weatherspark.com (As indicated in Figure 1).

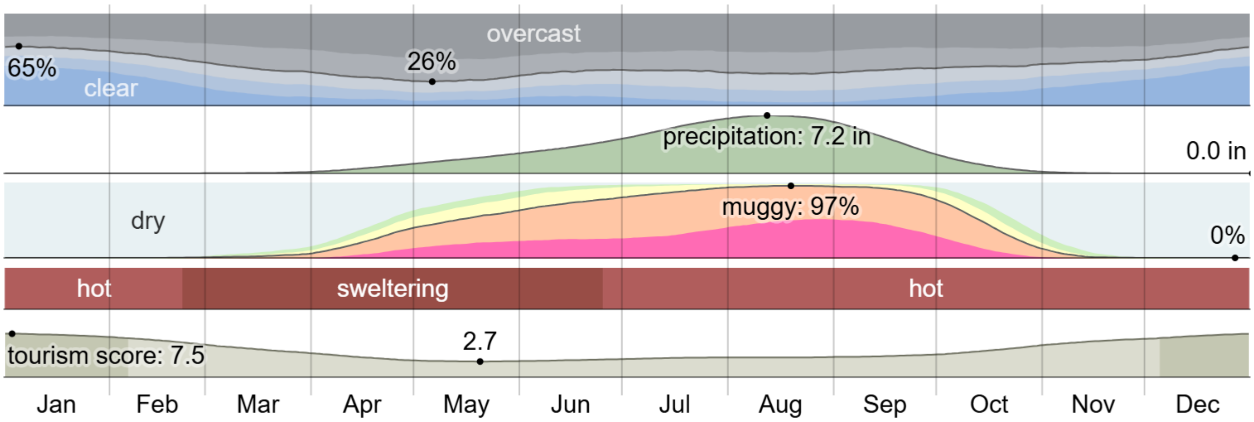

Figure 1. Seasonal weather pattern for Gaya, Kano State, showing mean monthly precipitation (inches), humidity, and temperature conditions during a typical year in the Sudan savannah zone. Source: adapted from WeatherSpark Climate Data, 2023.

Pre-plant soil samples (0–20 cm depth) were analyzed for physical and chemical properties following the methods of Anderson and Ingram (1993). The soil was a sandy loam, slightly acidic (pH 5.8 ± 0.2), low in organic carbon (0.62%), total nitrogen (0.07%), and available phosphorus (6.8 mg kg^{-1}). Exchangeable bases were Ca = 2.3, Mg = 1.6, K = 0.31 cmol kg^{-1}. The field had previously been under a millet–fallow rotation for two seasons before the experiment.

Experimental Design: A split-plot design arranged in a randomized complete block with three replications was used. The main-plot factor consisted of three bambara groundnut genotypes: Cream Brown Eye, Cream Black Eye, and Mottled Brown Eye. The subplot factor comprised three plant population densities established through different intra-row spacings:

a) S_1: 160 × 20 cm (10 plants m^{-2} = 320,000 plants ha^{-1})
b) S_2: 160 × 30 cm (8 plants m^{-2} = 240,000 plants ha^{-1})
c) S_3: 160 × 40 cm (6 plants m^{-2} = 160,000 plants ha^{-1})

Each main plot measured 12 × 4 m and was subdivided into three subplots (4 × 3 m). Genotypes were randomly assigned to main plots within each block, and plant densities were randomly allocated to subplots. Blocks were laid out perpendicular to the field slope to account for potential fertility gradients. Each subplot was considered an experimental unit. Each subplot measured 4 m × 3 m, and treatments were randomly assigned within blocks.

Planting Material and Crop Management
Seeds of the three genotypes were obtained from the Legume Germplasm Unit of the International Institute of Tropical Agriculture (IITA), Kano Station. Before planting, seeds were hand-sorted for uniformity and treated with wood ash to deter soil-borne pests. Land preparation involved plowing and harrowing to a fine tilth. Sowing was done manually on 8th July, 2023, placing two seeds per hill at a depth of 3–4 cm, and later thinned to one plant per stand at 3 weeks after sowing (WAS) to achieve the target density. A basal application of single superphosphate (SSP) fertilizer was made at 30 kg P_2O_5 ha^{-1} by side placement at 2 WAS. No nitrogen fertilizer was applied. Weed control was carried out manually at 3 and 6 WAS. The crop relied entirely on rainfall, and no chemical pest or disease control was necessary, as field inspection showed no major infestation. All plots were harvested manually at physiological maturity (approximately 100 days after sowing) when 80–90% of pods had turned brown.

Data Collection
Five representative plants were randomly selected from the central rows of each subplot (border plants excluded) for periodic measurements at 4, 6, and 8 WAS; Plant height (cm): measured from the base to the terminal bud using a meter rule, Number of leaves per plant: counted manually on each selected plant and Petiole length (cm): measured from the leaf axil to the base of the terminal leaflet on the third fully expanded leaf using a flexible ruler.

At maturity, the same five plants were harvested for component analysis; the Number of pods per plant and the number of seeds per pod were counted manually. The seed weight (100 g) was determined from air-dried seeds using an electronic balance (12% moisture basis). Grain yield (t ha^{-1}) was computed from total seed weight per plot, adjusted to 12% moisture content, and extrapolated to a hectare basis.

i. Shelling percentage (%) was calculated as:
$$= \frac{\text{Seed weight}}{\text{Pod weight}} \text{X } 100$$
ii. Productivity index was expressed as:
$$= \frac{\text{Grain Yield X Shelling percentage}}{100}$$

Statistical Analysis: All data were subjected to analysis of variance (ANOVA) for a split-plot design using the Statistical Tool for Agricultural Research (STAR v2.0.1, IRRI, 2023). Data were tested for normality (Shapiro–Wilk) and homogeneity of variance (Levene's test) before analysis. Treatment means were compared using the Student–Newman–Keuls (SNK) test at 5% probability.

Results and discussion
Plant height was significantly influenced by genotype and plant density at 4 weeks after sowing (WAS), though the differences diminished by 8 WAS (Table 1). The widest

spacing (160 × 40 cm) produced the tallest plants across all genotypes, whereas the densest spacing (160 × 20 cm) restricted vertical growth. At 4 WAS, Cream Brown eye had the tallest plants (19.75 cm), significantly taller than Mottled Black eye (17.27 cm), but Cream Black eye (18.16 cm) was statistically similar to both. at 6 and 8 WAS, no significant differences (NS) among genotypes. This inverse relationship between plant height and density reflects reduced interplant competition for photosynthetically active radiation, soil moisture, and nutrients under wider spacings, a pattern consistent with previous reports in legumes, such as soybeans and groundnuts (*Wang et al.*, 2023; *Iddrisu et al*., 2024). Similar morphological plasticity has been observed in bambara groundnut under density stress, where plants elongate internodes under lower competition to optimize canopy light interception (*Tan et al*., 2020). The coefficient of variation for plant height decreased from 10.59% to 5.65% across the sampling periods, indicating an increase in stand uniformity as plants matured.

Table 1: Effect of spacing on the plant height of three bambara groundnut genotypes

Treatment	**Plant height (cm)** 4 WAS	6 WAS	8 WAS
<u>Genotypes</u>			
Cream Brown eye	19.75^{a}	22.02^{b}	25.23^{a}
Cream Black eye	18.16^{ab}	21.86^{b}	25.02^{a}
Mottled Black eye	17.27^{b}	19.91^{b}	23.40^{ab}
S.E	0.92	0.72	0.65
<u>Spacing (cm)</u>			
160 × 20	19.71^{bc}	22.31^{b}	25.37^{a}
160 × 30	17.76^{c}	21.13^{b}	24.63^{a}
160 × 40	17.1^{c}	19.39^{bc}	23.33^{b}
C. V (%)	10.59	7.17	5.65

WAS = weeks after sowing. Means with the same letter (s) do not differ significantly at 5% level of significance. * Significant at 5% level (p<0.05), ** highly significant (p<0.01). Ns = Not significant.

Leaf number and petiole length showed significant difference on both genotype and spacing (Table 2). Cream Brown Eye exhibited the highest number of leaves (29.97 leaves plant^{-1} at 8 WAS), followed by Cream Black Eye, while Mottled Brown Eye consistently had fewer leaves. Leaf production increased significantly at moderate spacing (160 × 30 cm) compared to the widest (160 × 40 cm), suggesting that intermediate densities optimize canopy expansion without excessive self-shading. These findings align with those of Alhassan *et al*. (2012) and Essel *et al.* (2024), who reported that moderate spacing improved photosynthetic efficiency and biomass accumulation in bambara groundnut and cowpea under semi-arid conditions.

Petiole length followed a similar trend to plant height, with longer petioles recorded under wider spacings. This adaptation enhances light capture by extending the leaf lamina above neighboring plants (Wan et *al.,* 2023). Although the genotypic differences were not statistically significant, Cream Brown Eye showed a tendency toward longer petioles and greater canopy spread, suggesting greater morphological plasticity. Such variability among landraces underscores bambara groundnuts' genetic diversity, a critical trait for adaptation under variable agroecological conditions (Zhu *et al.,* 2021; Ruzive *et al.,* 2025).

Table 2: Temporal pattern and Genotypic Differences in Leaf Number per Plant and Petiole Length of Bambara Groundnut under Different Spacing

	Leaf Number		**Petiole Length**	
Genotypes	4 WAS	8 WAS	4 WAS	8 WAS
Cream Brown eye	12.55^{c}	29.97^{a}	11.56^{b}	16.42^{a}
Cream Black eye	11.22^{c}	29.53^{a}	9.44^{c}	14.83^{a}
Mottled Brown eye	8.93^{d}	24.09^{b}	8.88^{c}	13.25^{ab}
S.E	0.97	2.37	0.67	0.82
Spacing (cm)				
160 × 20	13.67^{c}	31.20^{a}	12.50^{b}	17.20^{a}
160 × 30	13.3^{c}	29.87^{a}	9.28^{c}	15.64^{a}
160 × 40	8.56^{d}	23.40^{b}	8.64^{c}	13.80^{ab}
C.V (%)	18.79	18.08	14.33	11.45

Means with the same letter (s) within column do not differ significantly at 5% level of significance

Pod number, seed weight, and shelling percentage differed significantly among both genotypes and spacings (Table 3). Mottled Brown Eye recorded the highest pod number (27.6 pods plant^{-1}) and shelling efficiency (82.4%), while Cream Brown Eye produced the heaviest seeds (52.7 g 100 seeds^{-1}). The moderate spacing (160 × 30 cm) consistently produced superior values across all yield components, suggesting an optimal balance between individual plant productivity and total stand yield. Dense plantings (160 × 20 cm) reduced pod and seed weights due to stronger competition for assimilates, while wide spacings (160 × 40 cm) lowered yield per area despite improved plant vigor.

Table 3: Yield components of three Bambara groundnut genotypes under different plant spacing

Treatment	Pods plant^{-1}	Seeds pod^{-1}	100-seed weight (g)	Shelling (%)
Genotypes				
Cream Brown Eye	26.4^{a}	1.65^{a}	52.7^{a}	78.3^{b}
Cream Black Eye	24.8^{ab}	1.60^{a}	51.2^{a}	80.1^{b}
Mottled Brown Eye	27.6^{a}	1.63^{a}	50.9^{a}	82.4^{a}
Spacing (cm)				
160 × 20	24.2^{b}	1.58^{a}	50.8^{b}	79.2^{b}
160 × 30	28.5^{a}	1.67^{a}	53.4^{a}	81.7^{a}
160 × 40	25.1^{b}	1.61^{a}	51.0^{ab}	79.5^{b}
S.E	1.12	0.05	0.87	1.21
C.V (%)	8.94	4.76	6.02	5.31

Means with the same letter(s) within a column do not differ significantly at 5% level of significance. ($p < 0.05$); NS = not significant.

The superior performance of Mottled Brown Eye in shelling percentage suggests better pod filling and partitioning efficiency traits associated with drought resilience and sink strength (Ruzive *et al.,* 2025). Higher productivity index values at moderate spacing further support the physiological efficiency of intermediate densities in balancing vegetative and reproductive sinks. This parabolic response between density and yield has been widely reported in grain legumes, including groundnut (Iddrisu *et al.,* 2024) and cowpea (Kamara *et al.,* 2018), reflecting the trade-off between per-plant yield and population productivity. Grain yield peaked at 1.85 t ha^{-1} under the intermediate spacing (160 × 30 cm), corresponding to approximately 8 plants m^{-2} (Table 4). This confirms that moderate plant populations maximize yield efficiency under limited-resource environments, as also observed by Ruzive *et al.* (2025) in Sudan and by Ajeigbe *et al*. (2024) in northern Nigeria.

Table 4: Combined yield performance and efficiency index of three bambara groundnut genotypes under different plant spacing

Treatment	Grain yield (t ha^{-1})	Shelling (%)	Productivity Index*
Genotypes			
Cream Brown Eye	1.85^{a}	78.3^{b}	1.45^{a}
Cream Black Eye	1.78^{ab}	80.1^{b}	1.43^{ab}
Mottled Brown Eye	1.81^{a}	82.4^{a}	1.49^{a}
Spacing (cm)			
160 × 20	1.62^{b}	79.2^{b}	1.28^{b}
160 × 30	1.85^{a}	81.7^{a}	1.51^{a}
160 × 40	1.43^{c}	79.5^{b}	1.14^{c}
S.E	0.06	1.03	0.04
C.V (%)	8.17	5.12	7.45

*Productivity Index = (Grain yield × Shelling efficiency) ÷ 100. Means with the same letter(s) within a column do not differ significantly at 5% level of significance.= significant at 5% ($p < 0.05$); NS = not significant.

The results highlight the sensitivity of bambara groundnut performance to plant density and genotype-by-environment interactions. In semi-arid environments like the Sudan savannah, moderate spacing (8 plants m^{-2}) allows better soil moisture use efficiency and canopy aeration, which are critical for reproductive success under high evaporative demand (Bamshaiye *et al.*, 2011). Wider spacing beyond this threshold reduces stand density and overall yield potential, while denser stands intensify competition and shading effects. These findings underscore the need to integrate genotype selection with agronomic optimization to exploit bambara groundnuts' full potential as a climate-resilient crop.

Yield density of Bambara groundnut exhibited a clear density-dependent response, with all genotypes attaining maximum yield at the intermediate spacing (30 cm), followed by declines at both closer (20 cm) and wider (40 cm) spacings (Fig. 2). The reduced yield under closer spacing likely reflects intensified intra-specific competition for light, nutrients, and moisture, whereas wider spacing lowers yield primarily through reduced plant population per unit area. Such quadratic yield responses to plant density are widely reported in grain legumes and Bambara groundnut, where optimum spacing balances canopy development and resource-use efficiency (Azam-Ali *et al.*, 2001; Massawe *et al.*, 2005). The superior performance of Cream Brown Eye across spacings suggests inherent genotypic differences in resource-use efficiency and yield stability, consistent with earlier reports highlighting strong genotype × density interactions in Bambara groundnut production systems (Azam-Ali et al., 2001; Massawe et al., 2005).

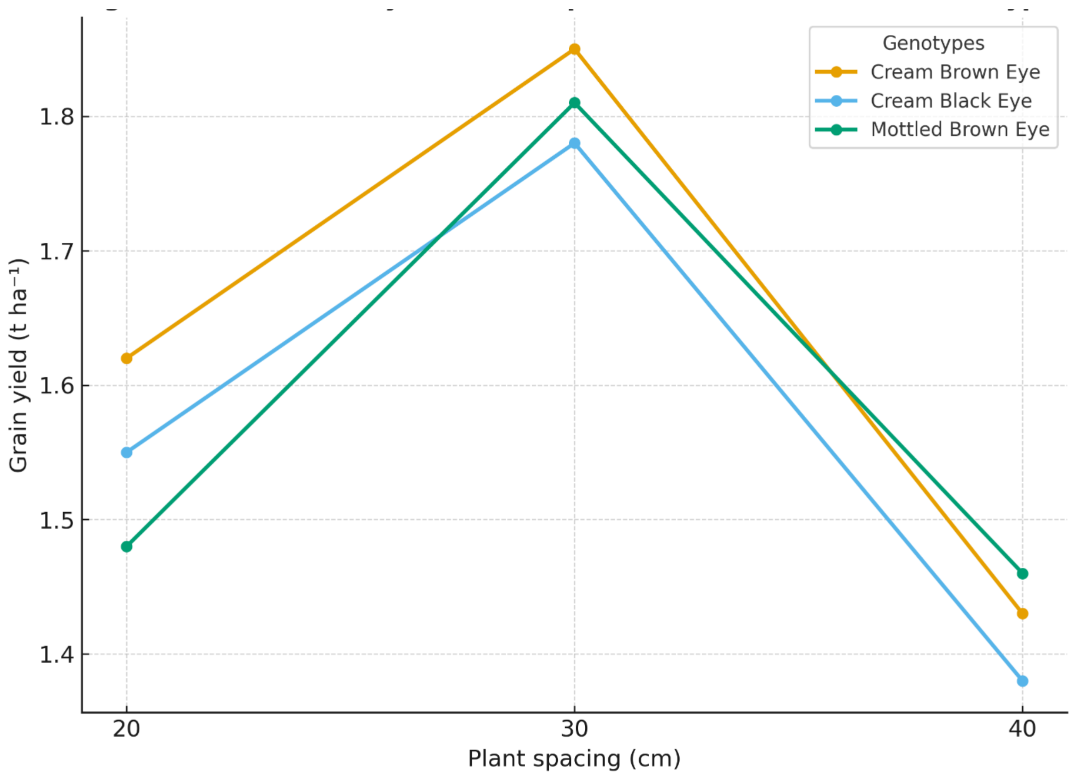

Figure 2. Yield-Density Relationship of Bambara Groundnut Genotypes: Illustrating the parabolic trend of the peaks at the intermediate spacing (160 × 30 cm) for all genotypes.

Conclusion

This study demonstrates that bambara groundnut growth and yield performance are strongly influenced by plant density and genotype. Lower densities promoted greater vegetative growth (plant height and petiole elongation), while moderate densities (approximately 8 plants m^{-2}; 160 × 30 cm) produced the highest pod number, seed weight, and grain yield across genotypes. Among the tested landraces, Mottled Brown Eye showed superior shelling efficiency and yield stability, highlighting its adaptability to the Sudan savannah environment. The results suggest that adopting moderate plant populations enhances light interception, minimizes intra-plant competition, and maximizes yield per unit area. These insights provide a practical basis for developing density-specific agronomic recommendations for bambara groundnut cultivation in semi-arid West Africa.

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