



INTRASPECIFIC VARIATION AND EFFECTS OF SEED RATE PER HILL ON THE MORPHOLOGICAL AND YIELD COMPONENTS OF BAMBARA GROUNDNUT (*Vigna subterranea* [L.] Verdc.)

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ABSTRACT: Current world challenges in Bambara groundnut cultivation remained investigative with climatic change, limiting the agronomic and yield potentials. There is need to determine the optimal seed rate per hill for Bambara groundnut improvement. This becomes imperative to ensure efficient utilization of genetic resources, as request for seeds from genebanks come with limited seeds. Ten accessions were sourced from IITA, Ibadan. The experiment was laid out in a 10 × 2 factorial arranged in Randomized Complete Block Design (RCBD), replicated 3 times. Two (2) seeds and One (1) seed were planted per hill in a raised bed. The data was subjected to GLM procedure in Statistical Analysis Software (SAS), and significant difference was determined using Tukey HSD at P<0.05 and 0.01. Number of pods per plant and pod length were significantly different for one seed per hill. These two traits were significantly higher for one seed per hill indicating an efficient genetic resources utilization, and the need for further investigation. Principal Components 1–5 constituted 71.10% of the total relatedness. This study showed that nine traits are key traits to relatedness and diversity, and should be considered in the selection of parents in future research.

Keywords: Accessions, Climate change, Morphology, Seed rate, and Variation.

INTRODUCTION

Bambara groundnut (*Vigna subterranea*) is a native legume crop found in Africa, known for its good nutritional value and economic importance (Majola *et al.*, 2021). There are challenges in creating new hybrids of this crop because of the cleistogamous nature of the flower. However, improving the way it is grown is very important to make the most of what it can offer. The number of seeds planted is a key factor that affects the crop growth and production. Using the ideal number of seeds per hill helps make optimum use of available plant genetic resources, reduces competition between plants, and performance (Khan *et al.*, 2021). Seed rate per hill is a very important

aspect of plant breeding (Lübberstedt *et al.*, 2023), it enhances fair chance of each accession to thrive, hence, over competition does not affect the expression of optimum performance in plants. Seed rate per hill gives adequate plant population, and ensure that phenotypic expression is true representation of the accession. Despite, the crucial role seed rate per hill plays in breeding programmes, there is not much research done on how it affects the production of Bambara groundnut. Most studies focus on other parts of growing this crop, such as choosing the best varieties, improving soil quality, and managing pests. Hence, farmers often use traditional methods with different seed rates per hill, which can lead to over competition in plants and lower production. Bambara groundnut helps increase the productivity of farms and improves the health of the soil (Chimonyo *et al.*, 2020; Tan *et al.*, 2020). Its ability to survive in dry conditions, pests, and diseases makes it possible to grow it on less-fertile land, supporting efforts to adapt to climate change

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and restore land (Soumare *et al.*, 2021; Khan *et al.*, 2021). Despite having good agronomic and nutritional qualities, growing Bambara groundnut is usually done in small-scale farming systems where modern farming methods are not widely used. Because of this, traditional farming methods are still commonly used and can vary a lot from one area to another. As a result, crop productivity is often low and not improving without better plant varieties or better farming practices (Muhammad *et al.*, 2020; Couzins, 2022). Focusing on important research areas, like figuring out the best seed rate per hill, can help make Bambara groundnut more useful for food security, help farmers grow more types of crops, and create better job opportunities for poor farmers in sub-Saharan Africa and other regions (Couzins, 2022; Maphosa *et al.*, 2022). These low yields are mostly because of poor farming practices, such as not knowing the ideal number of seeds to plant or how to space the plants (Temegne *et al.*, 2020; Umeugokwe *et al.*, 2021). Traits such as number of pods, seed weight, and how much biomass plants produce are all affected by how densely the plants are grown, which depends on seed rates per hill and how the plants are arranged in the field (Akohoue *et al.*, 2020). However, the exact ways seed rates per hill or seed rate per hectare affect crop growth are still not fully understood, and existing farming advice is often general and not suited for specific types of local plants or farming systems (Temegne *et al.*, 2018; Akohoue *et al.*, 2020).

This study wants to evaluate how number of seeds planted in a hill affects the growth and production of Bambara groundnut. It also aims to find out the morphological traits such as pod length, number of pods per plant, pod width, and 100-seed weight among 10 accessions of Bambara groundnut influences its yield. It also aims to reveal the similarity and differences in the morphological traits for selection. The results will help farmers and scientists improve Bambara groundnut farming and support food and nutrition security.

MATERIALS AND METHODS

Study area

This study was carried out at the Research Field of the Federal University Oye-Ekiti (Ikole campus), Ekiti State, Nigeria with Longitude 07°N 48.550' and Latitude 005°E 29.788'. The area is a tropical rainforest characterized by eight rainy months in a year (April-November) with an average rainfall of 1500 mm/yr.

Seed collection

Ten accessions of Bambara Groundnut were sourced from the Genetic Resource Center, International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. The accessions were selected based on broad genetic diversity as reported by Osundare *et al.*, 2023.

Experimental design and agronomic practices

The experiment was laid down in a 10 × 2 factorial arranged in a Randomized Complete Block Design (RCBD) and replicated 3 times. (10 accessions and 2 seed rates). The seed rates were 2 seeds per hill (2/hill) and 1 seed per hill (1/hill). Plot Size was 1 m by 0.5 m and a total of 60 plots was made to contain all the replicates in the 2023/2024 and 2024/2025 cropping seasons. Two seeds and One seed were planted per hill in a raised bed. Manual weed approach such as hoe weeding was employed. Number of plants per plot was 15. Inter and intra-row spacing was 0.25 m × 0.25 m, and inter plot spacing was 1 metre.

Data collection

Ten plants were tagged for data collection. The descriptor list of Bambara groundnut as developed by IITA/IPGRI, 2000 was used to generate data (IPGRI/IITA, 2020). Observed traits include plant height, terminal leaflet length, terminal leaflet width, number of pods per plant, pod length, pod width, seed length, seed width, 100-seed weight, Average Terminal leaflet per plot, Petiole length, Seed yield per plot, Pod wall thickness, and chaff weight.

Data analysis

The data was subjected to General Linear Model (GLM) procedure in Statistical Analysis Software (SAS) and Tukey's HSD was used to separate means for observed agronomic traits, and significant difference was determined using Tukey HSD at P<0.05 and 0.01. Principal component analysis (PCA) was used to identify the pattern of variation and traits loadings, and considered where eigen factor is ≥ 1. Pearson correlation was carried out using the PROC CORR procedure to indicate the association of yield components.

RESULTS

The Analysis of variance (ANOVA) revealed highly significant differences for 7 traits at two seed rates, out of the 14 quantitative traits evaluated (Table 1). The mean value of the accessions studied revealed that terminal leaflet width (TLL, cm) varied significantly from 2.77 to 4.14, while accessions TVSu-1635, TVSu-112, TVSu-595, TVSu-1717 had the highest terminal leaflet width under two seeds per hill and accessions TVSu-12, TVSu-1171, also had higher terminal leaflet width under one seed per hill. Petiole length (PL, cm) varied significantly from 13.16 to 21.59; accessions TVSu-1717 had the longest petiole length under one seed rate per hill and TVSu-595 had higher petiole length at two seed per hill. 100 seed weight varied significantly from 67.66 to 102.99; accessions TVSu-542 had the highest seed weight at one seed/hill and TVSu-1633 had the highest at two seed/hill. Number of pods per plant (PP) varied significantly from 19.33 to 45.33; accessions TVSu-1171 had the highest number of pods per plant at one seed/hill while accessions TVSu-12 had the highest number of pods per plant at two

seeds/hill. Seed length (SL, mm) varied significantly from 3.82 to 8.18; accessions TVSu-112 had the longest seed at one seed/hill while accessions TVSu-1130 had the longest seed length at two seeds/hill. Seed width (SW, mm) varied significantly from 4.09 to 6.36; accessions TVSu-112 had the widest width at one seed/hill and at two seeds/hill. Pod length (PdL, mm) varied significantly from 11.77 to 19.67; accessions TVSu-595 had the longest pod length at one seed/hill while accessions TVSu-1633 had the longest pod length at two seeds/hill. Analysis of variance for seed rate per hill indicated that pod length and number of pods per plant had significant differences in the observed traits (Table 2). Pods per plant varied significantly for the two seeding rates per hill (1/hill and 2/hill), one seed per hill (1/hill) had 29.70 and two seeds per hill (2/hill) had 26.66. Pod length also varied significantly for the two seeding rates per hill, one seed per hill had 14.49 mm and two seeds per hill had 16.11 mm respectively.

Principal components

Comparison of the principal component's (PC) contribution to relatedness revealed that PCs 1–5 constitute 71.10% of the total relatedness, where PCs 1, 2, 3, 4 and 5 contributed 32.30, 12.60, 10.40, 8.50, and 7.20 respectively (Table 3). PCA showed PC1 constituted 32.30 % and PC2 constituted 12.60 %, while the first five PCs that had eigen values ≥ 1 revealed 71.10% of total relatedness. Higher contribution to total relatedness among the accessions was revealed by PCs 1 and 2. PC1 contributed 32.30%; these traits contributed positively (Figure 1 and 2) (Table 3) to the relatedness for plant height (0.076), terminal leaflet length (0.223), terminal leaflet width (0.068), terminal leaflet per plot (0.022), petiole length (0.128), pod length (0.382), pod weight per plot (0.408), chaff weight per plot (0.39), and 100-seed weight (0.438), while seed yield per plot (-0.044), number of pods per plant (-0.02), seed length (-0.26), seed width (-0.413), and pod width (-0.162) contributed negatively to the variation. PC2 contributed 12.60 %, with the

component of Terminal leaflet per plot (0.189), seed length (0.022), pod length (0.083), pod wall thickness (0.039) contributing positively to the variation while plant height (-0.286), terminal leaflet length (-0.136), terminal leaflet width (-0.277), petiole length (-0.263), seed yield per plot (-0.613), number of pods per plant (-0.07), seed width (-0.041), pod width (-0.549), chaff weight (-0.156), and 100-seed weight (-0.036) contributed negatively (Fig. 1 and 2) (Table 3).

Correlation coefficients

Correlation coefficients revealed that pod length had a positive and significant correlation with pod wall thickness ($r = 0.68$), 100-seed weight ($r = 0.78$). Pod wall thickness revealed positive and significant correlation with chaff weight ($r = 0.69$), 100-seed weight ($r = 0.79$) and chaff weight with 100-seed weight ($r = 0.77$). Negative and significant correlation was observed for seed width and pod length ($r = -0.65$), pod wall thickness (-0.70), chaff weight (-0.64) and 100-seed weight ($r = -0.80$) (Table 4).

Cluster analysis of quantitative traits

Cluster analysis was used to assess the level of variation of the observed quantitative traits, individuals with related traits are grouped into the same cluster. The similarity and distance of the accessions used are the foundation of this method, determined by its similarity and distance coefficient levels, where similar accessions were grouped into the same cluster and dissimilar accessions were grouped differently.

The length between the lines was calculated using standardized morphological data, and a dendrogram was constructed using these values (Fig. 3). The traits exhibited similarity in the selected population ranging from 9.88 to 89.67. The similarity level revealed that nine of the traits showed similarity level at 71.10 %. This revealed that 9 out of the 14 traits had linkage as revealed through the similarity coefficients.

Table 1: Mean performance of 10 accessions of Bambara groundnut under two seed rates

Accessions	Observed Characters													
	PH cm		TLL cm		TLW cm		TLP		PL cm		SWP g		100-SDW g	
	Seed rates													
	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds
TVSu-112	24.37a	26.45a	6.33a	6.02a	2.92b	3.63ab	47.66a	48.00a	13.16b	14.54b	25.48a	25.73a	81.57abc	75.90bc
TVSu-1130	26.83a	27.35a	6.68a	6.27a	2.97b	3.00b	49.00a	46.00a	15.57b	15.22b	26.79a	22.50a	70.18bc	74.61bc
TVSu-1171	27.53a	26.02a	6.65a	6.49a	3.15ab	3.04ab	48.00a	47.00a	14.94b	14.77b	28.21a	20.95a	75.77bc	77.07bc
TVSu-12	25.71a	25.99a	6.12a	6.26a	3.38ab	2.77b	47.00a	47.66a	13.56b	14.00b	26.90a	32.49a	67.66c	67.70c
TVSu-1633	26.74a	26.18a	6.98a	6.55a	3.37ab	3.00b	49.66a	50.66a	14.53b	14.08b	27.20a	23.61a	77.07bc	102.99a
TVSu-1635	24.89a	24.93a	6.28a	6.31a	3.22ab	4.14a	49.66a	51.33a	13.50b	14.08b	32.19a	21.69a	78.40bc	89.44abc
TVSu-1717	24.37a	27.57a	6.07a	6.56a	3.23ab	3.08ab	47.16a	47.66a	21.59a	14.80b	22.00a	24.16a	73.07bc	73.57bc
TVSu-225	25.80a	25.49a	6.43a	6.18a	3.04ab	2.82b	46.66a	48.66a	14.14b	14.32b	23.31a	24.04a	68.43c	71.18bc
TVSu-542	26.14a	25.21a	6.55a	6.42a	3.20ab	3.00b	50.66a	48.00a	16.44b	14.30b	34.24a	26.43a	93.26ab	73.28bc
TVSu-595	25.65a	25.90a	6.37a	6.32a	3.22ab	3.13ab	48.00a	49.50a	13.19b	14.24a	23.87a	21.24a	70.76bc	73.55bc

Legend: PH=Plant height, TLL=Terminal leaflet length, TLW=Terminal leaflet width, TLP=Average Terminal leaflet per plot, PL=Petiole length, SWP=Seed yield per plot, 100-SDW=100-seed weight (g)

Legend: PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight

Table 1 cont'd: Mean performance of 10 accessions of Bambara groundnut under two seed rates

Accessions	Observed characters													
	PP		SL mm		SW mm		PDL mm		PDW mm		PWT mm		CW g	
	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds	1 seed	2 seeds
TVSu-112	28.33bc	21.33bc	8.18a	7.96a	6.36a	6.23a	17.84ab	18.11ab	13.24a	12.80a	0.69a	0.71a	9.39a	8.64a
TVSu-1130	25.33bc	21.66bc	5.06ab	8.22a	5.67ab	6.22b	13.39ab	16.02ab	11.78a	11.88a	0.58a	0.78a	8.81a	8.48a
TVSu-1171	36.50ab	21.66bc	3.97b	3.82b	5.42ab	5.82ab	12.17ab	13.70ab	15.62a	14.41a	0.76a	0.80a	9.57a	8.99a
TVSu-12	33.33abc	45.33a	6.94ab	7.61ab	5.31ab	6.12ab	13.59ab	13.82ab	11.18a	13.44a	0.71a	0.73a	8.48a	8.99a
TVSu-1633	26.66bc	23.00bc	6.57ab	4.62ab	5.60ab	4.09b	13.89ab	19.67a	14.48a	12.71a	0.75a	1.00a	9.92a	12.95a
TVSu-1635	28.33bc	26.16bc	5.17ab	6.43ab	5.79ab	5.10ab	13.67ab	19.26ab	14.18a	12.36a	0.80a	0.95a	12.92a	9.03a
TVSu-1717	26.16bc	22.33bc	5.72ab	5.90ab	5.09ab	4.83ab	15.24ab	15.62ab	10.30a	11.77a	0.67a	0.63a	7.99a	9.28a
TVSu-225	33.00abc	30.66abc	5.54ab	5.03ab	5.16ab	5.25ab	11.77b	14.52ab	12.51a	15.07a	0.63a	0.66a	8.44a	8.67a
TVSu-542	27.66bc	19.33c	5.02ab	6.26ab	4.98ab	5.83ab	15.36ab	14.57ab	19.09a	14.43a	0.76a	0.63a	10.50a	8.64a
TVSu-595	31.66abc	35.16ab	7.18ab	7.00ab	5.53ab	5.68ab	17.99ab	15.81ab	12.15a	11.80a	0.69a	0.70a	8.96a	9.02a

Legend: PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight

Means followed by the same superscript letter within a column are not significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Table 2: Mean performance of 10 accessions of Bambara groundnut as affected by seed rates per hill

Characters														
Seed rate	PH cm	TLL cm	TLW cm	TLP	PL cm	SWP g	PP	SL mm	SW g	PDL mm	PDW mm	PWT mm	CW g	100-SDW g
1/hill	25.80a	6.44a	3.17a	48.35a	15.06a	27.02a	29.70a	5.93a	5.49a	14.49b	13.45a	0.70a	9.50a	75.62a
2/hill	26.11a	6.34a	3.16a	48.45a	14.44a	24.28a	26.66b	6.28a	5.52a	16.11a	13.07a	0.76a	9.27a	77.93a

Means followed by the same superscript letter within a column are not significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Legend: PH=Plant height, TLL=Terminal leaflet length, TLW=Terminal leaflet width, TLP=Average Terminal leaflet per plot, PL=Petiole length,

PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight

SWP=Seed yield per plot, 100-SDW=100-seed weight

Table 3: Eigen values and contribution of first five principal components axes to variation

Variable	PC1	PC2	PC3	PC4	PC5
Eigenvalue	4.5197	1.7617	1.4616	1.196	1.0103
Proportions	0.323	0.126	0.104	0.085	0.072
Cumulative	0.323	0.449	0.553	0.638	0.711
PH cm	0.076	-0.286	-0.131	0.27	0.376
TLL cm	0.223	-0.136	-0.608	0.208	-0.05
TLW cm	0.068	-0.277	0.67	-0.182	-0.053
TLP	0.022	0.189	-0.181	-0.581	-0.131
PL	0.128	-0.263	0.157	0.263	0.417
SWP	-0.044	-0.613	-0.223	-0.236	-0.203
PP	-0.02	-0.07	-0.131	-0.569	0.521
SL	-0.26	0.022	0.033	0.155	-0.394
SW	-0.413	-0.041	-0.127	-0.018	-0.134
PDL	0.382	0.083	0.011	0.076	-0.254
PDW	-0.162	-0.549	0.051	-0.034	-0.232
PWT	0.408	0.039	0.095	-0.098	-0.066
CW	0.39	-0.156	-0.087	-0.154	-0.171
HSW	0.438	-0.036	0.06	0.003	-0.155

Legend: PH=Plant height, TLL=Terminal leaflet length, TLW=Terminal leaflet width, TLP=Average Terminal leaflet per plot, PL=Petiole length, SWP=Seed yield per plot, PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight, HSW=100-seed weight

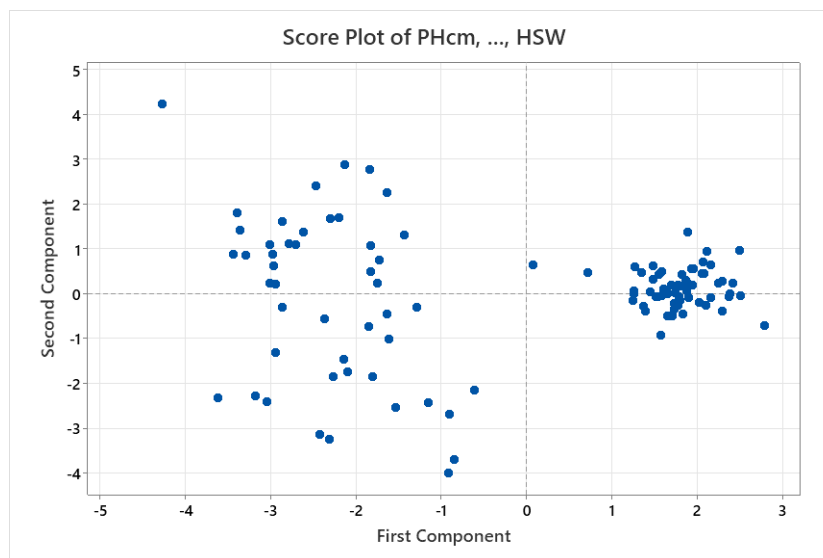


Figure 1. Scree plot distribution showing traits contribution in component 1 and 2

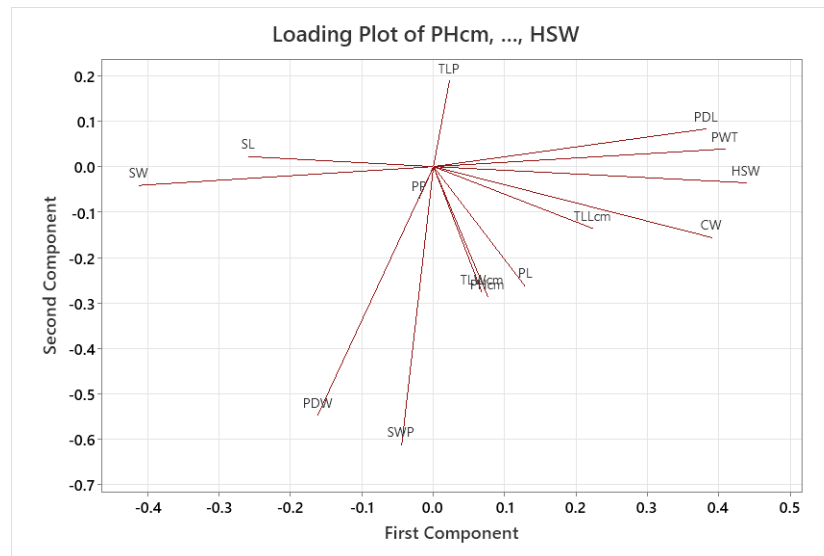


Figure 2. Cluster analysis of PH cm, TLL cm, TLW cm, TLP, PL, SWP, PP, SL, SW, PDL, PDW, PWT, CW, HSW

Table 4: Correlation coefficient of agronomic and yield traits of 10 accessions of Bambara groundnut

Variables	PH cm	TLL cm	TLW cm	TLP	PL	SWP	PP	SL	SW	PDL	PDW	PWT	CW
PH cm	1												
TLL cm	0.217	1											
TLW cm	0.065	-0.404	1										
TLP	-0.095	-0.012	-0.092	1									
PL	0.108	0.112	0.154	-0.141	1								
SWP	0.135	0.215	0.118	-0.019	0.09	1							
PP	-0.006	-0.031	-0.016	0.066	-0.043	0.182	1						
SL	-0.096	-0.246	-0.047	-0.132	-0.195	0.102	-0.05	1					
SW	-0.142	-0.291	-0.194	0.011	-0.249	0.213	0.01	0.528	1				
PDL	0.054	0.362	0.077	0.019	0.115	-0.132	-0.102	-0.234	-0.656*	1			
PDW	0.063	-0.076	0.205	-0.111	0.034	0.507	-0.057	0.083	0.292	-0.289	1		
PWT	0.094	0.277	0.211	0.039	0.141	-0.076	0.014	-0.387	-0.702*	0.689*	-0.358	1	
CW	0.105	0.426	0.128	0.097	0.174	0.193	0	-0.405	-0.642*	0.585	-0.154	0.699*	1
HSW	0.082	0.401	0.196	0.011	0.22	-0.062	-0.078	-0.412	-0.802*	0.785*	-0.217	0.793*	0.778*

* significant @ $P \leq 0.05$

Legend: PH=Plant height, TLL=Terminal leaflet length, TLW=Terminal leaflet width, TLP=Average Terminal leaflet per plot, PL=Petiole length, SWP=Seed yield per plot,

PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight, HSW=100-seed weight

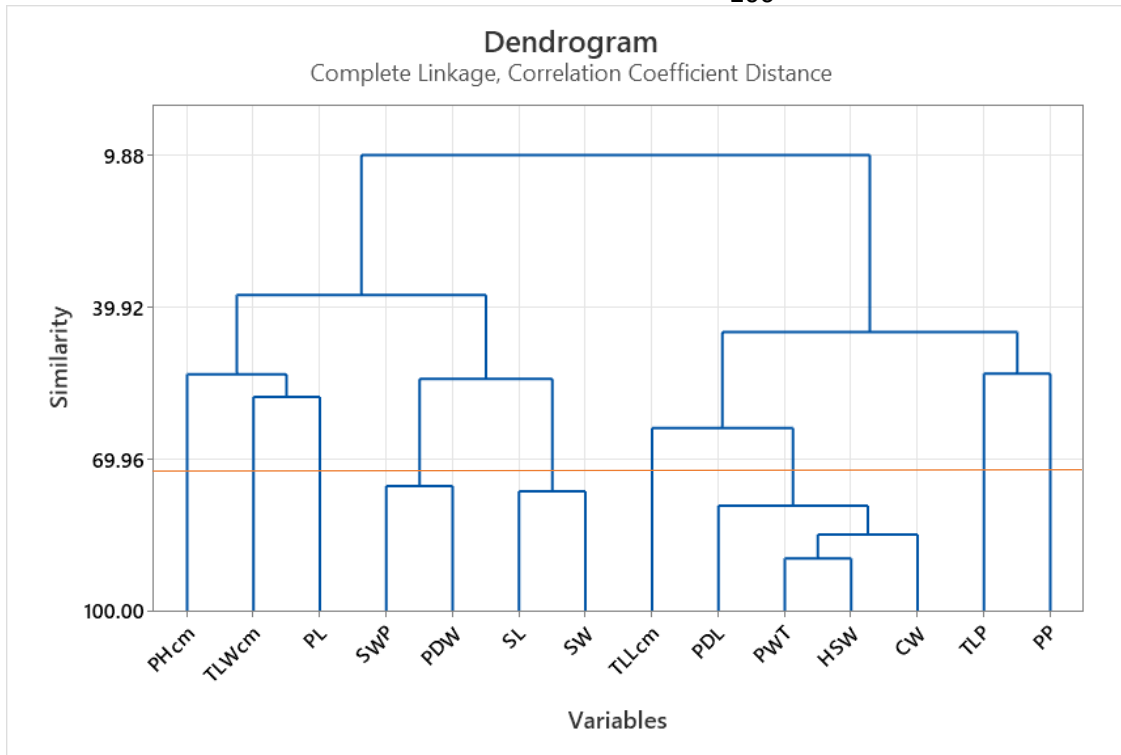


Figure 3. Dendrogram showing complete linkage of variables based on correlation distances

Legend: PH=Plant height, TLL=Terminal leaflet length, TLW=Terminal leaflet width, TLP=Average Terminal leaflet per plot, PL=Petiole length, SWP=Seed yield per plot, PP=Pods per plant, SL= Seed length, SW=Seed width, PDL=Pod length, PDW=Pod width, PWT=Pod wall thickness, CW=Chaff weight, HSW=100-seed weight

DISCUSSION

The present study demonstrated appreciable intraspecific variation among the ten Bambara groundnut accessions and showed that the effect of seed rate per hill was trait-dependent. Of the 14 quantitative traits evaluated, significant differences between one and two seeds per hill were detected only for number of pods per plant and pod length. This indicates that most morphological and yield-related traits were relatively stable across the two planting rates under the conditions of the study, whereas pod production and pod elongation were more responsive to intra-hill plant density. Plants established with one seed per hill produced significantly more pods per plant than those established with two seeds per hill (29.70 versus 26.66 pods plant⁻¹). The higher pod number under the single-seed treatment may be associated with reduced intra-hill competition for light, water, nutrients and assimilates. Reduced competition may promote canopy development, flowering, pegging and pod filling, thereby increasing the number of pods retained per plant. This finding agrees with the report of Uba *et al.* (2022), who observed variation in pod production among Bambara groundnut landraces grown under different planting

arrangements. Since pod number is an important component of grain yield in Bambara groundnut, its improvement may contribute substantially to yield enhancement. Alake *et al.* (2015) similarly identified number of pods per plant as an effective selection criterion for improving grain yield and yield stability in Bambara groundnut.

In contrast, pod length was significantly greater at two seeds per hill than at one seed per hill (16.11 and 14.49 mm, respectively). This contrasting response suggests that increased intra-hill competition did not uniformly reduce reproductive performance. Although competition may have reduced the number of pods produced per plant, the assimilates available to individual pods may have been distributed in a manner that favoured pod elongation. Alternatively, the observed difference may reflect accession-specific responses or variation in pod development among the genotypes. The absence of a significant seed-rate effect on seed yield per plot and 100-seed weight indicates that the differences in pod number and pod length did not translate directly into differences in final yield under the conditions of this experiment.

Consequently, pod number should be interpreted as a useful selection trait, but not as a sole indicator of yield performance. The accessions differed significantly for several traits, including terminal leaflet width, petiole length, 100-seed weight, number of pods per plant, seed length, seed width and pod length. These differences confirm the presence of useful phenotypic diversity within the evaluated germplasm. For example, TVSu-1717 showed the longest petiole under one seed per hill, TVSu-595 had the longest petiole under two seeds per hill, TVSu-542 recorded the highest 100-seed weight under one seed per hill, and TVSu-1633 had the highest 100-seed weight under two seeds per hill. TVSu-1171 produced the greatest number of pods per plant under one seed per hill, whereas TVSu-12 produced the highest pod number under two seeds per hill. Such accession-specific responses highlight the importance of evaluating genotypes under the intended agronomic conditions rather than assuming that a single seed rate will be optimal for all accessions. Similar phenotypic variation in yield components and seed traits has been reported in Bambara groundnut collections by Khan *et al.* (2020, 2021), Muhammad *et al.* (2020), Osundare *et al.* (2023) and Uba *et al.* (2022). The lack of significant differences among accessions for plant height, terminal leaflet length, seed yield per plot, pod width, pod wall thickness and chaff weight suggests that these traits were comparatively conserved in the material evaluated or were strongly influenced by the prevailing environmental conditions. The absence of significant differences should not, however, be interpreted as evidence of a complete absence of genetic variation. Environmental effects, experimental error and the relatively small number of accessions may have limited the detection of differences. Multi-location and multi-season evaluations would therefore be useful for determining the stability and heritability of these traits. The correlation analysis provided additional information on relationships among the measured traits. Pod length was positively and significantly correlated with pod wall thickness and 100-seed weight, while pod wall thickness was positively correlated with chaff weight and 100-seed weight. The strong positive association between pod length and 100-seed weight suggests that accessions with longer pods may also possess greater seed mass. Likewise, the positive relationship between pod wall thickness and 100-seed weight may indicate a common contribution of pod development and assimilate accumulation to seed size. These relationships may be useful in indirect selection, particularly where direct measurement of seed yield is difficult or requires destructive sampling. Nevertheless, correlation does not establish causation, and these associations should be validated in larger populations and across environments. Similar positive relationships among yield components have been reported by Halimi *et al.* (2021). Seed width showed significant negative

correlations with pod length, pod wall thickness, chaff weight and 100-seed weight. These relationships indicate an apparent trade-off between seed width and traits associated with pod size and seed mass in the evaluated accessions. Therefore, selection for wider seeds may not necessarily improve pod length or 100-seed weight. However, the direction and magnitude of correlations can vary with population structure, environment and trait measurement. Selection should consequently be based on a combination of traits and the specific breeding objective. The negative associations observed in this study are consistent with the reports of Muhammad *et al.* (2020), who emphasized the need to consider possible trade-offs among seed and pod traits when improving Bambara groundnut. Principal component analysis further confirmed the multidimensional nature of variation in the collection. The first five principal components, each with an eigenvalue greater than one, accounted for 71.10% of the total variation. PC1 explained the largest proportion of variation (32.30%) and was strongly associated, among other traits, with 100-seed weight, pod wall thickness, pod length, chaff weight and seed yield per plot. PC2 explained an additional 12.60% and was characterized mainly by variation in seed yield per plot, pod width and several vegetative traits. The relatively large contribution of PC1 and PC2 indicates that variation in seed size, pod characteristics, biomass-related traits and yield components constituted major sources of divergence among the accessions. The importance of the first principal components in describing diversity in Bambara groundnut has also been reported by Esan *et al.* (2023) and Mesay *et al.* (2022).

The trait loadings also showed that different components represented contrasting biological dimensions of the accessions. For example, 100-seed weight, pod length and pod wall thickness had positive loadings on PC1, whereas seed width and seed length had negative loadings. This pattern supports the correlation results and suggests that selection based on a single trait may result in unintended changes in other traits. The traits with large absolute loadings, including 100-seed weight, pod length, pod wall thickness, seed yield per plot, pod width, terminal leaflet traits and pod number, should therefore receive priority during characterization and parent selection. However, the contribution of a trait to a principal component should not be equated directly with its agronomic importance; the usefulness of each trait must also be assessed in relation to yield, stability, consumer preference and breeding objectives. Cluster analysis revealed morphological similarity as well as separation among the accessions. The grouping pattern indicates that some accessions shared similar combinations of quantitative traits, whereas others were more distinct. These groupings may reflect shared ancestry, adaptation to similar environments or convergence in phenotype. However, morphological

similarity alone cannot confirm common genetic ancestry because phenotypic traits are influenced by the environment. Molecular characterization would therefore be valuable for testing the genetic relationships suggested by the dendrogram and for identifying genetically divergent parents. The observed clustering is consistent with previous reports of substantial morphological and genetic diversity among Bambara groundnut accessions (Khan *et al.*, 2020, 2021; Muhammad *et al.*, 2020; Osundare *et al.*, 2023). From a practical perspective, planting one seed per hill produced more pods per plant and used fewer seeds while maintaining statistically similar values for seed yield per plot, 100-seed weight and most other traits. This supports the use of one seed per hill where the objective is to conserve limited breeding seed, reduce unnecessary intra-hill competition and improve the efficiency of germplasm evaluation. However, the recommendation should be interpreted cautiously because pod length was greater under two seeds per hill and total seed yield did not differ significantly between the treatments. Thus, one seed per hill may be considered an efficient establishment rate for germplasm multiplication and preliminary evaluation, but its superiority for commercial production requires confirmation using larger plots, additional seasons, different spacings and a wider range of planting densities. Overall, the results demonstrate that both accession identity and seed rate per hill influence the expression of selected morphological and yield components in Bambara groundnut. Number of pods per plant, pod length, 100-seed weight, seed dimensions, petiole length and terminal leaflet width were particularly informative for describing variation and guiding selection. The combination of analysis of variance, correlation analysis, principal component analysis and clustering provides a useful basis for identifying promising parents and designing future Bambara groundnut improvement.

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studies. Further research should incorporate genotype × seed-rate interaction analysis, heritability estimates, multi-environment testing and molecular markers to distinguish genetically controlled variation from environmental effects.

CONCLUSIONS

This research concluded that one seed rate per hill (1/hill) at 0.25 m × 0.25 m is recommended for optimal yield and efficient use of plant genetic resources for Bambara groundnut production. The research evidently showed morphological similarities and differences existed among Bambara groundnut planted at one seed per hill and two seeds per hill, and that such variation existed in number of pods per plant, and pod length. These traits are important to improving Bambara groundnut and to optimize genetic resources utilization. The differences for 100-seed weight, terminal leaflet width, seed length, petiole length and seed width for the selected accessions are important traits that should be given consideration in making selection for parents and yield components in Bambara groundnut breeding.

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Data Availability

The data used to support the findings of this research are available from the corresponding author upon request.

Conflict of interest

The authors declare that they have no conflict of interest.

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