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Seed Morphometrics Characterization of African Bambara Groundnut (*Vigna subterranea L.)* Landraces

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ABSTRACT

The nutrient-dense Bambara groundnut is renowned for its ability to withstand extreme weather conditions. Its use is still restricted despite its potential because of problems such a hard seed coat, prolonged cooking times, and poor germination. In this study, a group of landraces from all over Africa was evaluated for genetic diversity in important seed-associated properties. Using a completely randomized approach with three replications, 60 genotypes were assessed for seed hardness, germination performance, and seedling vigor. R version 4.1.1 was used to analyze the data from the experiment, which was carried out at Jimma University College of Agriculture and Veterinary Medicine in Ethiopia. Each trait's broad-sense heritability and genetic and phenotypic coefficients of variation were calculated. For every evaluated attribute, the analysis of variance showed highly significant differences ($p<0.001$) between genotypes. Except mean germination time, every attribute showed significant heritability and genetic advancement, indicating limited environmental effect and strong additive genetic control. As a result, these qualities present excellent targets for breeding program selection. Interdependence between attributes was demonstrated by the positive and significant association between hundred-seed weight and seed length, width, thickness, electrical conductivity, and compression force, as determined by Pearson correlation analysis. These findings lay the groundwork for direct trait selection to increase seedling establishment and cooking quality in Bambara groundnuts.

Keywords: *Vigna subterranea*, seed hardness, germination traits, Seed vigour, underutilized legumes

INTRODUCTION

Despite its agronomic and nutritional significance, the African legume known as the "bambara groundnut" (Vigna subterranea L. Verdc.) is still neglected (Agajie, 2021). After cowpea (Vigna unguiculata) and peanut (Arachis hypogaea), it is the third most widely grown legume in Africa (Khan et al., 2021). Wild populations of this crop can be found from the Jos and Yola plateaus in Nigeria to Garoua in Cameroon and beyond. It is native to northeastern Nigeria and northern Cameroon (Olukolu et al., 2012). Since there aren't many improved varieties from official breeding efforts, Bambara groundnuts are mostly

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propagated through landraces (Aliyu et al., 2016). Small, rounded, and very rigid when dried, the seeds are usually encased in pods with one or two seeds that are 8–14 mm in diameter (Nandkangre et al., 2022). Because of its high protein content and low cost, this self-pollinating annual herbaceous plant that grows in marginal soils could be a solution for food and nutritional security in rural areas (Uba et al., 2022). From immature green seeds to completely dried grains, Bambara groundnuts can be eaten at different stages of development. According to Amarteifio et al. (2006) and Mune et al. (2011), the seeds are high in protein (19–25%), carbs (63%), fiber (6.5%), and important amino acids including leucine and lysine. In comparison to typical pulses such as cowpea, pigeon pea, and lentil, the crop has a higher gross energy content (FAO, 2018). Additionally, the leaves are utilized as fodder and the seeds are given to pigs and chickens (Gbaguidi et al., 2018). Some cultures regard Bambara groundnuts for their therapeutic properties in addition to their nutritional qualities (Atoyebi et al., 2018). However, the crop is still understudied, especially in terms of seed trait variation, despite its nutritional profile and climate adaptability (Mayes et al., 2019; Mabhaudhi et al., 2013). Finding variance in important agronomic variables to direct breeding efforts requires thorough analysis of genetic resources. Limited research has examined seed morphometric traits like germination efficiency, vigor, and hardness—traits that are essential for successful crop establishment, processing quality, and overall improvement—while the majority of previous studies have focused on agronomic performance and compositional analysis (Hillocks et al., 2012). Comprehending the phenotypic variations in these seed characteristics can help with selection procedures and reveal information about the genetic makeup of populations. Genetic indicators that provide crucial information for assessing variety and guiding breeding techniques include heritability, genotypic and phenotypic coefficients of variation (GCV and PCV), and genetic advance (GA). Designing effective breeding programs aimed at maintaining and exploiting valuable landraces requires knowledge of the genetic heterogeneity found in Bambara groundnut collections (Uba et al., 2023). Therefore, the purpose of this study was to use morphological descriptors to evaluate genetic variability in seed properties among various African Bambara groundnut landraces. In particular, the goals were to assess the variety of qualities connected to seeds, look at trait correlations, and find possible genotypes with soft seed coatings that would be helpful in breeding for better germination and cookability. The results are intended to close the existing knowledge gap between the diversity of seed traits and real-world uses in breeding program selection and seed quality enhancement.

MATERIALS AND METHODS

Plant Materials and Study Location

Sixty (60) genotypes of Bambara groundnuts from various genetic origins were obtained from the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria. The United Kingdom and fourteen African nations were the original sources of these accessions. The field trials were carried out at the Jimma University Research and Experimental Farm, which is situated in Ethiopia at 7°40′N and 36°50′E, during the 2020–2021 cropping season. With an average yearly rainfall of about, the location has a subtropical highland climate 1,500 mm.

Table 1 lists all genotypes and their respective countries of origin.

SN	GENOTYPES	COUNTRY OF ORIGIN
1	TVSu-1018	Zimbabwe
2	TVSu-1034	Zimbawe
3	TVSu-1064	Zimbawe
4	TVSu-1101	Zimbabwe
5	TVSu-1112	Zimbabwe
6	TVSu-1115	Zimbabwe
7	TVSu-12	Nigeria
8	TVSu-1237	Nigeria
9	TVSu-1305	Central African Republic

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SN	GENOTYPES	COUNTRY OF ORIGIN	SN	GENOTYPES	COUNTRY OF ORIGIN
10	TVSu-1307	Central African Republic	54	TVSu-770	Zambia
11	TVSu-1324	Central African Republic	55	TVSu-870	Zambia
12	TVSu-1362	Central African Republic	56	TVSu-893	Zambia
13	TVSu-1363	Central African Republic	57	TVSu-926	Zambia
14	TVSu-1364	Central African Republic	58	TVSu-939	Zambia
15	TVSu-1378	Centre African Republic	59	TVSu-987	Zimbabwe
16	TVSu-1380	United Kingdom	60	TVSu-990	Zimbabwe
17	TVSu-1700	Togo			
18	TVSu-1737	Zambia			
19	TVSu-1751	Malawi			
20	TVSu-1775	Malawi			
21	TVSu-1794	Malawi			
22	TVSu-1799	Malawi			
23	TVSu-1813	Cameroon			
24	TVSu-1821	Cameroon			
25	TVSu-1860	Zimbabwe			
26	TVSu-1872	Zimbabwe			
27	TVSu-193	Benin			
28	TVSu-1964	Swaziland			
29	TVSu-1999	DRC			
30	TVSu-200	Benin			
31	TVSu-2007	DRC			
32	TVSu-2008	DRC			
33	TVSu-2014	DRC			
34	TVSu-2074	Nigeria			
35	TVSu-2076	Nigeria			
36	TVSu-236	Ghana			
37	TVSu-242	Gambia			
38	TVSu-335	Nigeria			
39	TVSu-345	Nigeria			
40	TVSu-358	Nigeria			
41	TVSu-369	Tanzania			
42	TVSu-378	Tanzania			
43	TVSu-379	Tanzania			
44	TVSu-386	Tanzania			
45	TVSu-393	Sudan			
46	TVSu-600	Nigeria			
47	TVSu-688	Zambia			
48	TVSu-691	Zambia			
49	TVSu-702	Zambia			
50	TVSu-723	Zambia			
51	TVSu-725	Zambia			
52	TVSu-742	Zambia			
53	TVSu-762	Zambia			

Experimental Design and Trait Evaluation

Both greenhouse and lab tests used a completely randomized design (CRD) with three replications per genotype. Thirty seeds from each accession were chosen at random and measured for morphometric analysis using the Descriptors for Bambara Groundnut (IPGRI, 2000) as a guide.

Seed Dimensional Traits (cm)

A vernier caliper was used to measure the length, breadth, and thickness of the seeds. The distance along the hilum axis between the poles of the seed was used to measure its length. Thickness was measured perpendicularly across the seed, while width was measured from the hilum to the keel.

Hundred Seed Weight (g)

An analytical balance was used to weigh 100 randomly chosen seeds in three repetitions for each genotype. The hundred-seed weight was determined by taking the average of these weights.

Germination Test

Three replicates of ten seeds per genotype were used to evaluate germination. The seeds were placed on double-layered wet germination paper in Petri dishes after being surface-sterilized with 70% ethanol and 2% sodium hypochlorite. The dishes were re-moistening every two days while being cultured for ten days at 25°C in a germination chamber. Every day, the number of seeds that germinated (defined as having a radicle length of at least 2 mm) was counted, and on day 10, the ultimate germination percentage was noted. This is how the percentage germination was determined:

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Final germination percentage (%) = $\frac{\text{number of seeds germinated}}{\text{number of seeds sown}} \times 100$

Germination Vigour

At the conclusion of the germination period, measures related to seedling vigor were measured. Using a ruler and thread, five seedlings were chosen at random from each Petri dish to measure the lengths of the roots and shoots. Both dry and fresh biomass were noted. In accordance with ISTA (2012) guidelines, seedlings were oven-dried at 80°C for 72 hours to obtain dry mass. Zhu et al. (2010)'s approach was used to determine the Seed Vigour Index (SVI):

$$\text{SVI} = \text{Seedling height} \times \frac{\sum(\text{number of germinated seedlings by end of test period})}{\text{days after sowing}}$$

Mean Germination Time (Days)

Every day, the time it took for seeds to sprout was recorded. The formula outlined by Ellis & Roberts (1981) and Khan et al. (2010) was used to calculate Mean Germination Time:

$$\text{MGT} = \frac{\sum(n \times d)}{N},$$

where n = number of seeds germinated on day d, and N = total seeds germinated

Germination Rate Index (GRI)

GRI was computed based on Maguire's (1962) formula:

$$\text{GRI} = \frac{G1}{N1} + \frac{G2}{N2} + \ldots + \frac{Gn}{Nn}$$

where G = number of seeds germinated and N = number of days to germination for each count.

Electrical Conductivity

After weighing ten seeds from each genotype, they were steeped for twenty-four hours in fifty milliliters of distilled water. A conductivity meter (OAKLON, EUTECK Instruments) was subsequently used to measure the electrical conductivity of the seed leachate, which was then converted to $\mu S\ cm^{-1}g^{-1}$.

Seedling Emergence Test

This study was carried out in a greenhouse. In polythene bags, five seeds per replication (15 seeds total per genotype) were sowed at a depth of 3 cm. For 20 days, emergence was noted every day. A seed was deemed emerged when the tip of its leaf poked through the ground. The total number of emerging seedlings was then used to compute the emergence percentage.

Seed Hardness Test

A texture analyzer (Stable Microsystems, TA.XT-plus) was used to measure the hardness of the seeds. The seeds were preconditioned for 24 hours at 37°C to standardize the moisture content. A 5 mm probe calibrated with a 2 kg force was used to crush three replicates of 10 seeds per genotype. The analyzer's Exponent Software was used to record the force (in Newtons) needed to rupture each seed.

Statistical Analysis

The central tendency and variability of the assessed attributes were summarized using descriptive statistics (mean, maximum, and minimum). The "variability" package in R (version 4.1.1) was used to determine genetic parameters, including broad-sense heritability (H^2b), genetic advance (GA), genetic advance as a percentage of the mean (GAM), phenotypic coefficient of variation (PCV), and genotypic coefficient of variation (GCV). To find significant differences between genotypes, analysis of variance (ANOVA) was used. To minimize the dimensionality of the data and identify the traits that are most responsible for phenotypic variance, Principal Component Analysis (PCA) was utilized. Pearson's correlation matrix was used to analyze trait connections. To classify genotypes according to trait similarities, hierarchical cluster analysis was employed. All

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calculations were carried out in R using the appropriate programs, such as ggplot2, corrplot, and FactoMineR.

RESULT

The morphometric evaluation's findings showed that the sixty Bambara groundnut accessions varied significantly from one another.

Variation in Seed Morphological Traits

Significant phenotypic variety among the 60 Bambara groundnut genotypes was indicated by statistical analysis, which showed extremely significant differences ($p < 0.001$) across all evaluated variables. Table 2's summary statistics revealed wide variations among the assessed attributes. The lowest hundred seed weight (23 g), seed length (11.7 mm), and seed width (10 mm) were reported by genotype TVSu-1237, whereas the highest values in these categories were obtained by genotype TVSu-335 (78 g, 18.9 mm, and 16 mm, respectively). In TVSu-2074, the seed thickness was 4.2 mm, but in TVSu-2076, it was 9.0 mm. The electrical conductivity values in TVSu-987 and TVSu-725 ranged from 4.0 µS/cm/g to 193.2 µS/cm/g. In terms of emergence percentage (20%), germination rate index (0.13), and germination percentage (10%), TVSu-1018 performed the worst. TVSu-725, on the other hand, had the lowest seed vigor index (0.4), whilst TVSu-1362 had the greatest (22.5). In terms of seed hardness, TVSu-2074 displayed the maximum compression force (274.58 N), whereas TVSu-1821 had the lowest (55.01 N).

Table 2: Summary of Morphological traits across 60 accessions

Traits	Min	Max	Mean±Sem
HSW (g)	23 (TVSu-1237)	78 (TVSu-335)	46.54±3.0
SL (mm)	11.7 (TVSu-1237)	18.9(TVSu-335)	14.47±0.4
SW (mm)	10 (TVSu-1237)	16(TVSu-335)	11.85±0.4
ST (mm)	4.2(TVSu-2074)	9 (TVSu-2076)	7.08±0.3
EC	4.0(TVSu-987)	193(TVSu-725)	72.44±11.3
GP (%)	10(TVSu-1018)	100(TVSu-386)	72.44±8.8
GRI	0.13(TVSu-1018)	2.48(TVSu-345)	1.35±0.2
MGT	4.0 (TVSu-1034)	10(TVSu-2076)	5.86±0.4
SVI	0.4(TVSu-725)	22.5(TVSu-1362)	10.15±2.3
EMP (%)	20(TVSu-1018)	100(TVSu-12)	60.33±9.1
CFN (N)	55.01(TVSu-1821)	274.58(TVSu-2074	117.02±14.9
CT (Secs)	0.31(TVSu-702)	3.36(TVSu-393)	1.14±0.3

MIN=minimum, MAX=maximum, SEm = standard error of the mean, HSW=hundred seed weight in grammes, SL=seed length, SW=seed width, ST=seed thickness (all in millimetres) EC=electrical conductivity, GP=germination percentage (%) GRI=germination rate index, MGT=mean germination time, SVI=seed vigour index, EMP=emergence percentage (%), CFN=compression force (Newtons), CT=compression time (sec).

Principal Component and Variability of Bambara groundnut

The multidimensional phenotypic data was broken down into four main components using principal component analysis (PCA), which together accounted for 62.50% of the variability. PC1 alone was responsible for 45.4% of the variation, whilst PC2 was responsible for 17.1%. Two biplots were produced: an individual PCA that displayed the genotype distribution and a variable PCA (figure 1a) that showed the loading and correlations of traits. According to their contribution to the

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variation (loadings), the seed traits SVI (0.9427), GRI (0.9355), RL (0.8967), GP (0.8843), SDDWGT (0.8831), SDWGT (0.8645), and PL (0.8551) were linked to the PC1 for the traits (Figure 1a). PC3 contributed to the variance of EMP (-0.6162) and CT (-0.5494), whereas PC2 was impacted by SW (0.8797), SL (0.8773), ST (0.7127), and HSW (0.5989). CT variation is influenced by PC4 (0.8055). Table 3 displayed the corresponding loading for every variable. However, the PCA for each individual genotype showed that variables like PL, RL, EMP, and SDDWGT were linked with genotypes like TVSu-939, TVSu-1115, TVSu-1794, and TVSu-1794 in the positive axis of PC1. Genotypes like TVSu-2076, TVSu-725, and TVSu-1018 are associated with features that adversely load on the PC1 negative axis, specifically EC and MGT. Additionally, characteristics like ST, SL, SW, and HSW have an impact on PC2 genotypes like TVSu-335, TVSu-926, and TVSu-242. The first two axes do not adequately characterize genotypes that are close to the axis (e.g., TVSu-1999). Furthermore, Significant genetic variability was seen in traits with high PCV and GCV values (>20%), such as biomass components, vigour index, germination percentage, and seed weight. Mean germination time and compression time varied less than seed length, width, and thickness, which varied moderately. Eight characteristics, including as electrical conductivity, germination rate, emergence percentage, and seed size dimensions, had strong broad-sense heritability, although mean germination time had low heredity (27%). With the exception of mean germination time, which had a low value of 8.34%, and some seed size attributes, which had moderate values as indicated in Table 4, the majority of traits also showed substantial genetic advance as a percentage of the mean (GAM).

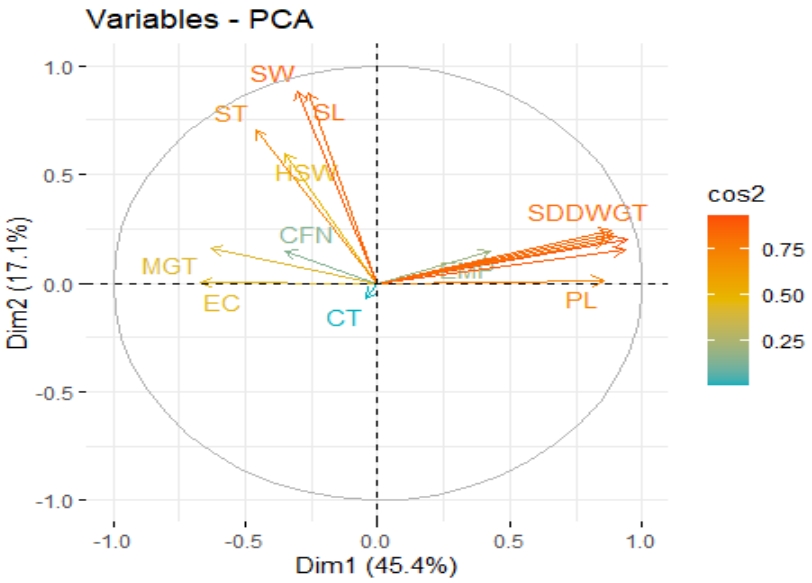

Figure 1a: Biplot of principal component analysis for traits

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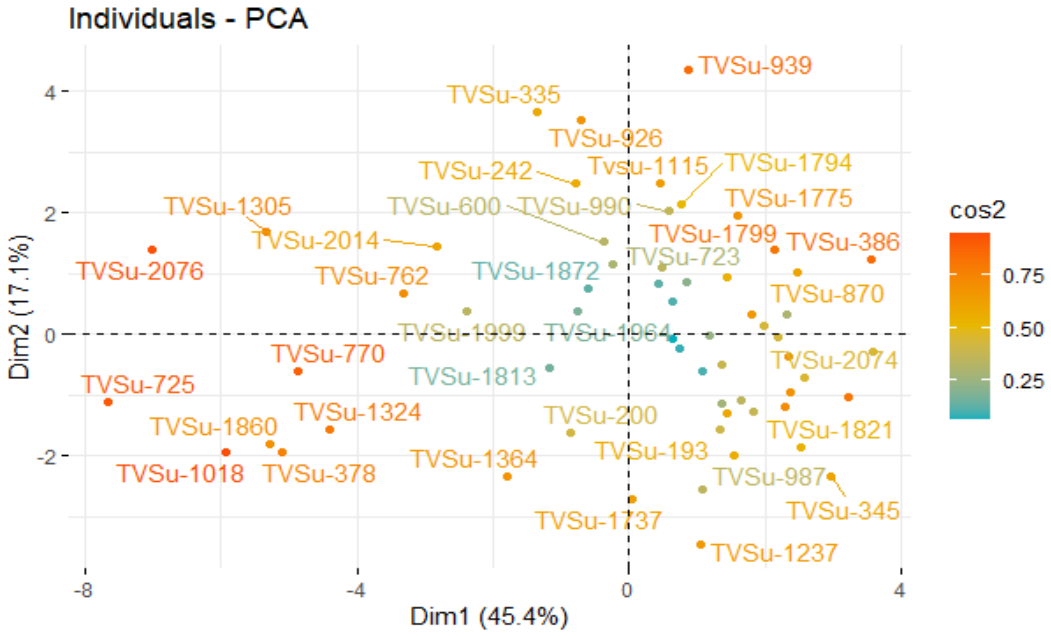

Figure 1b. Biplot of principal component analysis for Genotypes

Table 3: Dimension analysis table

Traits	PC1	PC2	PC3	PC4
HSW	-0.3572	**0.5989**	0.1506	-0.1296
SL	-0.2582	**0.8773**	-0.1070	0.0725
SW	-0.3067	**0.8797**	0.0406	0.0792
ST	-0.4631	**0.7127**	-0.0989	0.0711
EC	**-0.6726**	-0.0008	0.4052	0.0964
GP	**0.8843**	0.2272	-0.1073	-0.1557
GRI	**0.9355**	0.1657	-0.0144	-0.1004
MGT	**-0.6284**	0.1573	-0.3080	0.0428
SVI	**0.9427**	0.2012	0.0066	0.0421
SDWGT	**0.8645**	0.1998	0.2207	0.0933
SDDWGT	**0.8831**	0.2427	0.2323	0.1326
EMP	0.4265	-0.1491	**-0.6162**	-0.3633
RL	**0.8967**	0.2202	0.0288	0.2113
PL	**0.8551**	0.0146	0.2484	0.1358
CFN	-0.3924	0.1712	0.4751	0.2541
CT	0.0198	-0.0234	**-0.5494**	**0.8055**
Eigenvalue	7.2947	2.7541	1.3888	1.0154
Percentage variance	45.592	17.21335	8.6801	6.3462
Cumulative variance percent	45.592	62.8054	71.4855	77.8317

HSW=Hundred seed weight, SL=seed length, SW=seed width, ST=seed thickness, EC, Electrical conductivity, GP=Germination percentage, GRI = Germination rate index, MGT=Mean germination time, SVI=seed vigour index, SDWGT=Seedling wet weight, seedling dry weight, EMP=Emergence percentage, RL=Radicle length, PL=plumule length, CFN=Compression force in newton, CT=Compression Time in seconds.

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Table 4: Variation and genetic parameters among genotypes

TRAITS	GCV (%)	PCV (%)	H^2b (%)	GA	GAM
HSW	21.45	24.18	79	18.25	39.21
SL	7.97	9.3	73	2.03	14.05
SW	6.88	8.69	63	1.33	11.21
ST	9.91	12.78	60	1.12	15.82
EC	47.27	55.29	73	56.81	83.26
GP	29.46	36.19	66	36	49.41
GRI	34.52	43.82	62	0.76	56.02
MGT	7.74	14.79	27	0.49	8.34
SVI	37.2	53.7	48	5.39	53.08
SDWGT	30.86	47.68	42	0.83	41.14
SDDWGT	28.68	46.2	39	0.09	36.66
EMP	40	47.7	70	41.68	69.08
RL	25.68	40.79	40	2.47	33.3
PL	21.78	33.85	41	1.57	28.68
CFN	23.62	32.28	54	41.64	35.58
CT	0.15	0.44	34	58.19	40.23

GCV=genotypic coefficient of variation, PCV= phenotypic coefficient of variation, H^2b=broad sense heritability, GA=genetic advance, GAM=genetic advance as percent of mean, HSW=Hundred seed weight, SL=Seed length, SW=Seed width, ST=Seed thickness, EC=Electrical conductivity, GP=Germination percentage, GRI=Germination rate index, MGT=Mean germination time, SVI=Seed vigour index, SDWGT =seedling wet weight, SDDWGT =seedling dry weight, EMP=Emergence percentage, RL=radicle length, PL=plumule length, CFN=Compression force, CT=Compression time

Clustering analysis of genotypes to show Genetic Diversity

The 60 accessions were divided into three different clusters using hierarchical cluster analysis and 16 morphometric and physiological characteristics. With 32 genotypes (53.3%), Cluster 3 was the largest, followed by Cluster 2 (20 genotypes (33.3%) and Cluster 1 (8 genotypes (13.4%) (Figure 2). Distinct characteristic patterns were found across the groups using boxplot analysis (Figure 3). According to Figure 3(o-p), Cluster 1 genotypes displayed greater hardness and the longest compression time, whereas Cluster 3 genotypes exhibited the maximum seed hardness and the shortest compression time. Figure 3 (a-d) shows that Cluster 2 had the highest mean for hundred seed weight, length, width, and thickness, while Cluster 1 had the lowest mean for the previously mentioned parameters. Cluster 3 had the highest mean for germination and vigor, figure 3 (e-i, m-n), seedling biomass, and emergence, while cluster 1 had the lowest mean for these characteristics. figure 3 (l, j-k).

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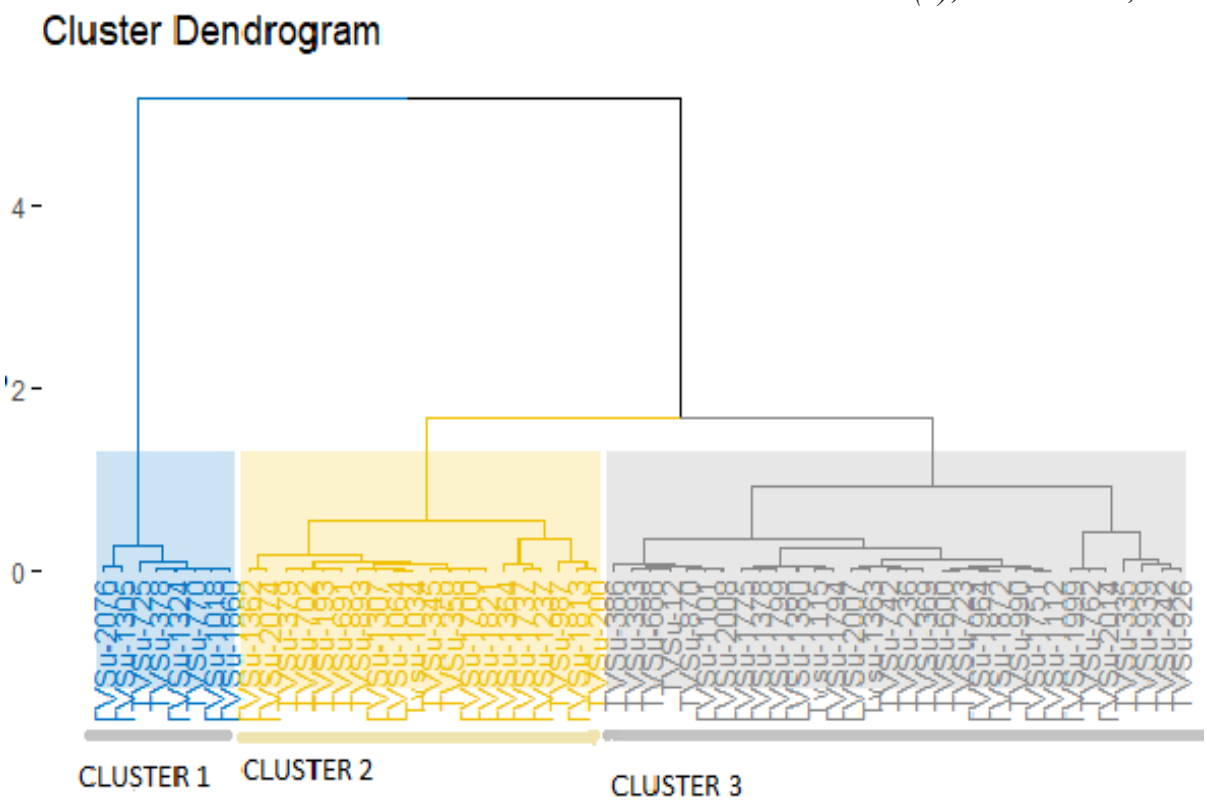

Figure **2**. Cluster analysis of the 60 **B**ambara nut genotypes

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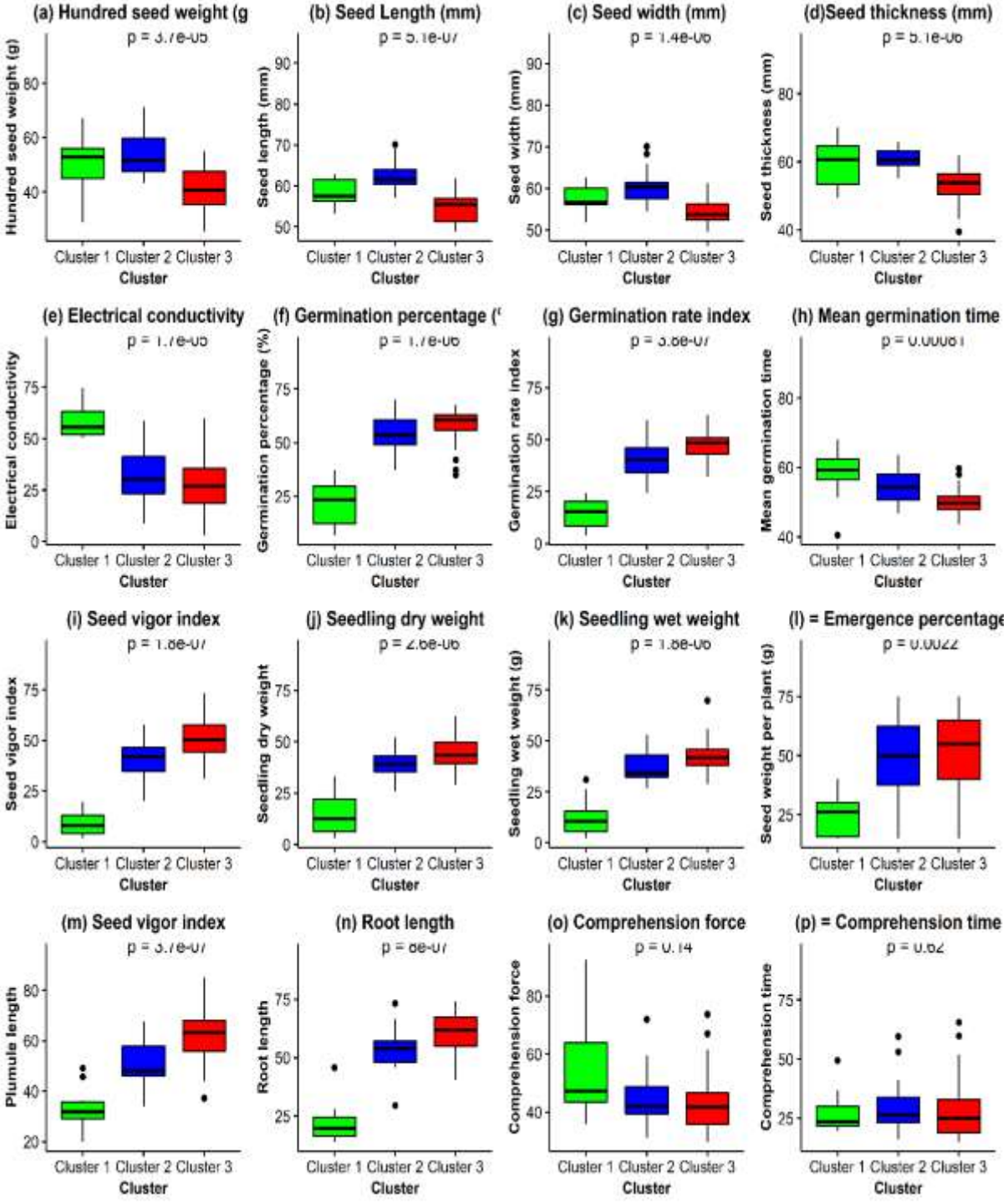

Figure 3: Comparative boxplot of mean seed traits for Bambara groundnut genotypes categorized into three clusters (green = cluster 1, blue = cluster 2 and red = cluster 3).

Association between Traits of Bambara Groundnut

A number of significant correlations were found using Pearson correlation analysis. The emergence rate (r = -0.32), germination percentage (r = -0.39), and seed vigour index (r = -0.41) all showed a significant negative connection with seed hardness, indicating that harder seeds often germinate more slowly and unevenly. On the other hand, the weight of 100 seeds had a high positive association with electrical conductivity, compression force, and seed size characteristics like length, breadth, and thickness (r = 0.66). Given that electrical conductivity and seed vigor indices have an

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inverse relationship, EC may be a valid measure of the physiological condition of seeds.

DISCUSSIONS

In line with earlier studies that emphasized the significant morphological diversity of this crop, the current analysis reveals a wide range of variation across the Bambara groundnut genotypes (Aliyu et al., 2016; Zango et al., 2023). Rich genetic variability is confirmed by the notable variations seen in all assessed seed attributes, providing important chances for crop development. These results support previous research by Onwubiko et al. (2019), which also found that Bambara groundnut accessions differed significantly in terms of seed vigor indicators. For breeding techniques, the positive correlations between some features are especially useful. Interestingly, the correlation between 100-seed weight and characteristics such as electrical conductivity, hardness, width, thickness, and length of seed implies that enhancing one property may also improve others. In line with findings in Bambara groundnut (Uba et al., 2022; Jonah, 2012) and African yam bean (Adewale et al., 2010), this association pattern suggests potential pleiotropy or close genetic linkage. These relationships may be due to genetic factors such linkage disequilibrium or epistatic interactions (Özer et al., 2010). One important component affecting germination and seedling establishment was found to be seed hardness. The limiting function of mechanical resistance and limited water intake in legumes was confirmed by genotypes with more stiff seed coats, which showed delayed or reduced germination capacity (Chandler et al., 2000). Further confirming EC as a reliable physiological indicator of seed quality, high electrical conductivity levels were also associated with poor seedling vigor, most likely as a result of membrane damage or solute leakage. A solid genetic foundation for important agronomic qualities, including as seed size, hardness, and germination traits, is suggested by the high heritability estimates found for these traits. Early breeding generations can successfully select for traits controlled by additive gene activity, such as those with high heritability and genetic advancement. However, characteristics with poor heredity, such mean germination time and seedling dry weight, could need more stringent selection techniques, like progeny testing or multi-location trials, to guarantee correctness. By dividing the genotypes into three different classes according to 16 assessed variables, the clustering analysis supported the observed phenotypic variety. The genotypes in Cluster 2 had bigger seed size dimensions, which is a crucial characteristic for seedling vigor and market preference. These findings are consistent with past research by Massawe et al. (2005) and Mayes et al. (2019), which highlighted the importance of seed size characteristics in the selection of Bambara groundnuts. Interestingly, Cluster 1 had the highest electrical conductivity readings, suggesting a damaged membrane and lower-quality seed. On the other hand, Cluster 3 was a useful group for breeding projects aiming for faster field emergence and better processing quality since it included accessions with soft seed coats and excellent germination indices, such as germination percentage, vigor index, and emergence rate. Berchie et al. (2010) and Pekşen et al. (2004) came to similar conclusions, stressing the significance of choosing genotypes that combine high germination potential with soft seed texture. Breeding variety with enhanced cookability and early seedling establishment is immediately possible using the genotypes in Cluster 3. Conversely, because hard-coated genotypes in Cluster 1 are linked to dormancy and poor emergence in the field, they would be less desirable (Mohammed et al., 2021). Future crossing programs can use these opposing characteristic patterns as a foundation for parent selection.

Conclusion

The results of this study show significant genetic and phenotypic variation among the 60 Bambara groundnut genotypes evaluated, especially in

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characteristics pertaining to hardness of the seed coat, germination, and seedling vigor. In order to better satisfy the demands of farmers and consumers, this diversity offers substantial opportunity for genotype selection and improvement. African landraces of Bambara groundnut have unique morpho-physiological characteristics, particularly in seed quality parameters, according to the study. High heritability and significant genetic advancement were demonstrated by traits such seed hardness, germination percentage, and vigor, indicating that these are primarily subject to additive genetic influence and are therefore excellent candidates for early-generation selection in breeding programs. Additionally, there is a chance for simultaneous improvement through multi-trait selection due of the strong trait interrelationships, such as those involving seed weight, seed dimensions, and vigor parameters. Based on seed quality profiles, genotypes were readily separated by cluster analysis. Cluster 3 offers immediate value for varietal modification focused at improving cookability and early seedling establishment since it contains soft-seeded accessions with high germination and vigor. Enhancing field performance and market acceptance requires these qualities. Despite being carried out in a controlled environment, this study was able to capture important features that are important for genetic progress. However, to confirm trait stability in field settings, future studies should investigate genotype × environment interactions. Furthermore, combining marker-assisted selection with genome-wide association studies (GWAS) may aid in identifying genomic areas associated with important agronomic properties, hastening the breeding of Bambara groundnut varieties that are both more nutritious and climate adaptable. This study contributes to the strategic development of Bambara groundnut as a climate-smart, sustainable crop for food and income security in sub-Saharan Africa and beyond by offering fundamental information on seed trait variation and performance.

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