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Original Research Article

Phenotypic diversity and path analysis of seed yield in Bambara groundnut grown in rain forest agroecological zone

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Abstract

Bambara groundnut is a reliable source of carbohydrates and protein in rainforest agroecology, but limited research had been done and few varieties commercialised. The magnitude of phenotypic variability, character association, and contribution of characters to seed yield were investigated among 50 accessions received from IITA, Nigeria. Field evaluation took place during the 2017–18 cropping seasons. The accessions were allocated to experimental plots using a Randomised Complete Block Design with three replicates. Data were collected on phenological, agronomic, and seed yield characters. The main effect showed significant ($p \leq 0.05$) differences for phenological, vegetative, and reproductive characters. The year effect influenced agronomic and seed yield characters while accessions by year interaction were insignificant for all characters. The stepwise discriminant analysis identified three redundant characters. The leaflet length and width, canopy spread, leaf/plant, seeds/plant, and seed weight showed high discriminatory ability and are efficient for morphological characterisation and conservation. Hybridisation between accessions dispersed in quadrants 1, 2, and 4 may evolve early and medium maturity types with improved seed yield and biomass. The number of seeds/plant and pods/plant are indices for seed yield. The contribution of pods/plant to seed yield was masked by canopy spread, peduncle length, and pod width indicating competition for photo-assimilates. TVSu 17, TVSu 277, TVSu 271, and TVSu 278 are donor parents for earliness. TVSu 261 performed best for seed yield and yield component characters. Hybridisation among TVSu 261, TVSu 587, TVSu 275, and TVSu 17 will evolve medium maturing and high seed-yielding varieties for further evaluation.

Keywords: *Vigna subterranea*; discriminatory ability; genotype × environment interaction; path analysis; seed yield; phenotypes

INTRODUCTION

Bambara groundnut (*Vigna subterranea* [L.] Verdc) is a drought-tolerant grain legume cultivated in drier regions in sub-Saharan Africa. It is an annual underutilised legume, its leaves are pinnately trifoliate, and flowering and fruit development are inhibited by long-day conditions. Flowering starts 30 to 35 days after sowing under short-day conditions. Bambara groundnut is an autogamous crop with cleistogamous flowers (Tindall, 1983; Azam-Ali et al. 2014). The annual production of Bambara groundnut is estimated to be 0.2 million tonnes from an area of 0.25 million hectares worldwide, and 0.14 million tonnes in 2020 from 0.18 million hectares in sub-Saharan Africa (FAOSTAT, 2020). The average seed yields of Bambara groundnut in Africa are between 300 and 800 kg/ha^{-1} (Brinks et al. 2006), between 0.56 and 0.80 t ha^{-1} and 28.90 g/plant in Nigeria (Olukolu, 2012) depending on the variety and production system but seed yields less than 100 kg/ha^{-1} on farmers' fields in sub-Saharan Africa had been documented (Brink et al., 2006). A seed yield of 0.1 million tonnes and unshelled yield of 3 t ha^{-1} was recorded from landraces grown in the transitional belt of Nigeria in 2020 (Smýkal et al., 2015) while production figures from the rain forest agroecology are limited. The average temperature between 20 °C to 28 °C, rainfall of 1100 to 1600 mm annually from sowing until flowering, and a soil pH of 5.0 to 6.5 are adequate for good growth and high seed yield (Hillocks et al. 2012; Azam-Ali et al. 2014). In Guinea, Sudan and Sahel agroecological zones field planting take place from October, through November to early December usually under late rainfall and irrigation. A little amount of precipitation is required for vegetative growth and flowering while harvesting coincides with the cold and dry season. Bambara groundnut has tolerance to poor soils and drought (Mabhaudhi and Modi; Rinawati et al., 2013), and it is a good legume in climate change mitigation (Hillocks et al. 2012). The matured seeds contain on average 10% water, 15–20% protein, 4–9% fat, 50–65% carbohydrate, and 3–5% fibre (Baudoin and Mergeai, 2001). The fresh Bambara leaves contain crude protein (15.9%), crude fibre (31.7%), ash (7.5%), and fat (1.8%) (Brink et al. 2006; Hilocks et al. 2012); this is important as fish feed. The morphological features of Bambara groundnut have been described by several authors (Doku and Karikari 1971; Linnemann, 1994; Goli, 1997; Uguru and Agwatu, 2006; Ntundu et al., 2006 and Khan et al., 2020), and hybridisation through conventional methods is slow (Goli et al. 1995); this limits progress in the development of new varieties (Marandu and Ntundu, 1995; Ntundu, 1997; Massawe et al., 2005; Uguru and Agwatu, 2006).

The knowledge of phenotypic diversity, trait association, and direct and indirect contribution of characters to yield and yield component characters among of Bambara groundnut germplasm have important roles in breeding programs for sustainable production. In addition, morphological characters which are highly correlated to grain yield give breeders the choice to make decisions as to which characters to select for when phenotypic improvement is in favour of seed yield (Karikari, 2000; Makanda et al., 2009; Breseghello and Coelho, 2013). Bambara groundnut is a traditional crop in Africa and many varieties are recognised differing in the shape of the leaves and size, hardiness and colour of the seeds, growth cycle (93 d–170 d) and pod maturity (120–150 d) (Mkandawire, 2007). The differences in soil moisture regime, temperature, and humidity and their influence on vegetative growth, and seed yield of Bambara groundnut in Nigeria (Saka et al., 2004; Jonah et al., 2010 and 2012) and in Botswana (Molosiwa, 2012) had been documented.

The phenotypic expression of a trait is determined by the interaction between the genotype and the environment. The measurement of phenotypic characters across environments (years) is imperative for identifying phenotypically stable and unstable characters. Correlation analysis tests the association between variables, this is not sufficient to measure the influence of independent variables on the dependent variable. As the number of independent characters affecting a dependent variable (seed yield) increases, interdependence occurs. This is essential for the indirect selection of characters that are not easily measured and have low heritability. The path analysis is a standardised partial regression coefficient that measures the direct or indirect influence of independent variables (morpho-physiological, phenological, and yield component characters) on seed yield (Kingsolver and Schemske, 1991). This is important for choosing characters that will increase seed yield through selection and simultaneous improvement of characters and determination of effective breeding procedures to improve seed yield. Bambara groundnut is not a traditional crop of the rainforest agroecology of Nigeria, where cassava, maize, cocoyam, and yam are stapled food crops and cocoa, oil palm, plantain, and cashew are largely cultivated. In addition, delay in onset of rainfall, inconsistent rainfall in terms of intensity and distribution in space and time, heat stress, early cessation of rainfall, and the implication of drought in the rainforest agroecology have increased the preference to cultivate Bambara groundnut.

Seed yield is an interaction of genotype and environment, and differential sensitivity to the environment (Smýkal et al., 2013). Bambara groundnut production in rainforest agroecology is constrained by the absence of commercial varieties, and the preponderance of insects and foliar diseases. Also, the soil is heavy and compact, which hinders the formation of pods in the soil and makes harvesting difficult. This research intends to use agro-morphological characters to evaluate the level and to analyse the organisation of the morpho-agronomic pattern of variation of the local population of Bambara groundnut to enhance conservation strategies and the use of these resources for the development of new varieties. Also, scale up cultivation and close the gap between market demand for grains and production, through the development of productive and stable varieties for growth and yield attributes for cultivation. A strategy to develop new varieties for this agroecology requires knowledge of morpho-physiological variation among the Bambara groundnut germplasm, interdependence between characters, and contribution of characters to seed yield, this may help to orient crop improvement plans. The objectives of this study were to; a) evaluate the magnitude of phenotypic variation among accessions of Bambara groundnut for agronomic, seed yield, and yield-component characters, b) determine phenotypic diversity for agronomic and seed yield characters, and c) evaluate the association between characters, and determine the direct and indirect effects of independent characters to seed yield. In this investigation, we evaluated morpho-physiological, agronomic, seed metric, and seed yield characters of *Vigna subterranea* [L.] Verdc with the following null hypothesis: (1) Bambara groundnut does not differ for morphological, agronomic, and seed yield characters, (2) there is no association between characters and no direct and indirect effects of eighteen causal variables on seed yield.

Table 1. Fifty accessions of Bambara groundnut collections from Nigeria

S/N	Accessions	S/N	Accessions
1	TVSU 586	26	TVSU 173
2	TVSU 180	27	TVSU 262
3	TVSU 605	28	TVSU 14
4	TVSU 263	29	TVSU 589
5	TVSU 12	30	TVSU 278
6	TVSU 283	31	TVSU 272
7	TVSU 606	32	TVSU 602
8	TVSU 178	33	TVSU 15
9	TVSU 16	34	TVSU 271
10	TVSU 592	35	TVSU 265
11	TVSU 588	36	TVSU 29
12	TVSU 181	37	TVSU 276
13	TVSU 256	38	TVSU 585
14	TVSU 275	39	TVSU 604
15	TVSU 171	40	TVSU 268
16	TVSU 261	41	TVSU 617
17	TVSU 590	42	TVSU 179
18	TVSU 264	43	TVSU 603
19	TVSU 13	44	TVSU 266
20	TVSU 22	45	TVSU 267
21	TVSU 11	46	TVSU 277
22	TVSU 280	47	TVSU 17
23	TVSU 587	48	TVSU 591
24	TVSU 601	49	TVSU 174
25	TVSU 280	50	TVSU 282

Sourced: IITA, Nigeria

MATERIALS AND METHODS

Germplasm and site characteristics

Fifty accessions (Table 1) of Bambara groundnut were collected from the Genetic Resources Unit, International Institute of Tropical Agriculture (IITA) in August 2016. Field experiments were carried out at the Teaching and Research Farm, Department of Crop Science and Horticulture, Federal University Oye Ekiti, Ikole Campus (Longitude 7°470°N and latitude 5°310°E) between August and December in 2017 and repeated in 2018. The experimental site has a bimodal rainfall regime; the rains commence in April and end in November annually, with a dry period in August. Between November and March is the dry season. Before the start of the experiment, soil samples were randomly collected from the experimental field from a depth of 0 cm to 25 cm. The samples were thoroughly mixed, air-dried and sub-samples submitted to the Department of Soil and Land Resources Management for laboratory analysis of physical and chemical properties. The soil pH (in H2O 1:1) was 5.7, organic matter was 0.82, N (%) 0.08, available phosphorus (Bray P method) 219.33, exchangeable Mg (cmol kg^{-1}) was 0.19, exchangeable K (cmol kg^{-1}) 0.48, exchangeable Na (cmol kg^{-1}) 0.07, exchangeable Ca (cmol kg^{-1}) 2.93, ECEC was 1.12, copper (cmol kg^{-1}) was 1.01, Mn (cmol kg^{-1}) 107.7, Fe (cmol kg^{-1}) 180.07, percent sand was 68, percent silt 20, percent clay 12 and textural class was sandy loam.

Experimental design and crop husbandry

The experimental area was 490 m^2, the field was plowed, harrowed, and ridged one meter apart. The accessions were allocated to experimental plots using a Randomised Complete Block Design (RCBD) with three replicates. Each accession was allotted to a plot of 5 m by 1 m, and fifty plots were maintained in a replicate. The sowing of Bambara groundnut seeds took place on 19th August 2017 and 20th August 2018 to coincide with the start of late season rainfall. Two seeds were sown per planting hole at a spacing of 0.30 m between plant and 1 m between rows, and 2–3 cm deep. Weeds were removed manually using hoes at 4, 8, and 12 weeks after planting (WAP). 20 ml of lambda Cyhalothrin EC® (WDG Corporations S.A, Switzerland) was dissolved in

Table 2. The morpho-physiological, agronomic, and seed yield characteristics recorded and brief description indicated in IPGRI, (2000)

Characters	Characters and description
Days to first flowering (d)	Number of days from sowing to when the first fully expanded leaf appears in a plot
Days to 50 % flowering (d)	Number of days from sowing to first flower opening on 50 % of plants per plot
Number of trifoliate/plant	Total number of leaves per plant at 10 weeks after planting (WAP)
Canopy spread (cm)	The widest point between two opposite points recorded at 10 WAP
Leaf chlorophyll	Determined at 30 d after planting using a chlorophyll meter machine (CCM-200 *PLUS*, Opti-Sciences, USA)
Leaflet length at (cm)	Length of the median leaflet at the fourth node recorded at flowering and 10 WAP
leaflet width (cm)	Width of the median leaflet at the fourth node recorded at flowering and 10 WAP
Plant length (cm)	Measured from the ground level to the tip of the highest point recorded at 10 WAP
Internode length (cm)	Length of the fourth internode of the longest stem, recorded at 10 WAP
Petiole length (cm)	Measured on 10 randomly picked plants at 10 WPA.
Root length (cm)	Measured at the longest point on 15 randomly picked plants/plots.
Petal length (cm)	Measured at the widest points on 15 randomly picked petals/plot.
Nodes/stem	Counted as the number of nodes on 10 randomly picked stems.
Branches/plant	Counted as the number of branches/plant.
Peduncle length (cm)	Recorded on the fourth internode of the longest stem recorded at 10 WAP.
Pod wall thickness (cm)	Determined on the pod wall of 100 randomly picked pods using Venier calipers.
Pods per plant	Counted from 5 randomly picked plants per plot within two months of harvest.
Pod wall weight (g)	The average weight of pod wall was taken from 5 plants per plot within two months of harvest.
Pod length (cm)	The average length of pod taken from 5 randomly picked plants per plot within two months of harvest.
Pod width (cm)	The average width of pod taken from 5 randomly picked pods per plant within two months of harvest.
Seeds per plant	The average number of seeds taken from 5 randomly picked plants per plot within two months of harvest.
Seed length (cm)	Average seed length was measured on 5 randomly picked seeds/plot using an electronic Venier caliper.
Seed width (cm)	Average seed width was measured on 5 randomly picked seeds/plot using an electronic Venier caliper.
Seed weight (kg)	This was determined by weighing dried seeds/plot at harvest on a weigh balance.

20 litres of water and sprayed at 5 WAP to reduce insect attacks and diseases. An organic fertiliser Super Gro fertilizer (Ethoxylated, Alkylphenol, and Polysiloxane, (manufactured by GNLD International, NAFDAC No: A5-0590) was applied at the rate of 100 ml in 100 litres of water at four and eight weeks after planting. Earthing-up was done manually at flowering using a hand-held hoe. The morpho-physiological, agronomic, and seed yield characteristics (Table 2) were measured following the descriptor list published for Bambara groundnut (IPGRI 2000) with slight modification. Chlorophyll content in each leaflet was determined at 30 days (d) after planting using a chlorophyll meter machine (CCM-200 PLUS, Opti-Sciences, USA) on 30 randomly sampled leaves for each accession over 3 replications. Harvesting was done manually using a hoe to lose the soil around the roots, followed by uprooting and shaking off the sand particles. The fresh pods were air-dried for 3 months, and dried pods were manually threshed to remove the seeds.

Data analysis

Agronomic characters were averaged over years and homogeneity of error variance was tested. The mean values were subjected to analysis of variance using SAS version 9.4 (SAS Institute Inc., 2012). Variance homogeneity was tested and a combined analysis of variance was performed using the generalised linear model (PROC GLM) procedure of SAS version 9.4 (SAS Institute Inc., 2012) to partition the total variation into components due to genotype (G), environment (E), and G × E interaction effects. Genotype was treated as a fixed

Table 3. a – Combined analysis of variance for phenological and vegetative characters in Bambara groundnut (*Vigna subterranea* [L.] Verdc) accessions during 2017 and 2018

Source of variation	Df	Days to first flowering (d)	Days to 50% flowering (d)	Leaf chlorophyll	Pod length (cm)	Leaflet length (cm) at flowering	Leaf width (cm) at flowering	Petiole length (cm)	Leaves /plant	Nodes /stem	Branches/ plant	Leaf length at maturity (cm)	Leaf width at flowering (cm)	number of trifoliate	Canopy spread (cm)
Genotype (G)	49	76.27**	80.99**	128.57**	20.41**	2.82**	0.52**	19.49**	16140.39**	1.06	2.50	2.91**	0.88**	1272.30**	103.18**
Replicate	2	1260.01**	58.17**	477.89**	29.56	7.42**	1.58**	2.26	3510.26**	2.54**	1.40	0.02	1.46**	1053.36**	102.22**
Year (Y)	1	2096.16**	52.06*	40.26	200.57	8.42**	1.60	0.002	11569.22**	5.33**	88.56**	5.96**	1.01**	921.41*	164.25**
G × Y	49	15.22	5.61	2.53	0.61	0.21	0.03	0.002	221.89	0.06	1.39	0.06	0.04	22.36	1.06
Error	198	245.12	5.84	55.98	10.49	0.79	0.24	2.16	386.63	0.09	2.27	1.08	0.26	144.45	3.34
Mean		45	52	47.67	3.24	6.27	2.04	12.52	163.96	2.00	2.76	6.30	2.31	54	15.96

*, **, *** significant at 0.05, 0.01 and 0.001 %, level of probability, respectively, ANOVA

b – Combined analysis of variance for agronomic and seed yield characters in Bambara groundnut (*Vigna subterranea* [L.] Verdc) accessions during 2017 and 2018

Source of variation	Df	Petal length (cm)	Peduncle length (cm)	Internode distance (cm)	Plant length (cm)	Root length (cm)	Pods /plant	Pod width (cm)	Seed length (cm)	Seed width (cm)	Pod wall Weight (g)	Pod wall thickness (cm)	Seed yield/ plant (g)	Seed weight/ plot (Kg)
Genotype (G)	49	82.27**	9.90*	0.72**	11.14*	189.14**	155.45**	0.30**	53.18**	0.08*	98.61**	0.03	2562.21**	0.08**
Replicate	2	3.08	0.27	0.20	12.09	372.17*	1.56	0.19	62.85	1.004*	192.45**	0.071	3893.31**	0.17**
Year (Y)	1	5.61	5.90	0.07	0.01	0.001	0.002	0.003	0.0005	0.01	1.23	0.003	15432.71**	0.06
G × Y	49	0.30	0.04	0.006	0.001	0.0008	0.001	0.007	0.0004	0.001	0.53	0.01	154.64	0.01
Error	198	2.29	3.56	0.27	5.95	99.46	33.08	0.14	26.28	0.04	35.77	0.03	826.21	0.04
Mean		15.39	3.31	1.28	6.29	7.81	12.38	1.09	1.29	0.68	7.09	0.17	41	2.23

*, **, *** significant at 0.05, 0.01 and 0.001 %, level of probability, respectively, ANOVA

effect and environment as a random effect. Multiple comparisons of the main effect were performed by Tukey's HSD test. Since the accession × year interaction was statistically insignificant for all characters, the mean values were subjected to discriminant analysis using PROC STEP DISC procedure (SAS Institute, 2012). The significance level of 0.001 of an F test from the analysis of covariance was used to choose discriminating characters (SAS Institute, 2012). Wilk's lambda (λ) was used as a criterion to determine the classification efficiency for each trait. The selected characters were used in the Principal component analysis (PCA) using PROC PRIMCOMP of (SAS Institute, 2012) to identify orthogonal directions of maximum variance in the original data set. The accessions were clustered by a dissimilarity distance matrix and the UPGMA (unweighted pair group method using arithmetic averages) clustering algorithm procedure (PROC FASTCLUST and PROC CLUSTER) to estimate similarities among the accessions. The Path co-efficient analysis described by Dewey and Lu (1959) was used to determine the direct and indirect effect of independent agronomic and seed yield component characters on seed yield. This was done using the PROC Coli procedure of (SAS Institute, 2012). Seed weight was considered as the response variable, while other characters that recorded a positive correlation coefficient with seed yield were causal variables. Lenka and Mishra (1973) rated values for direct and indirect effect into negligible (0.00–0.09), low (0.10–0.19), moderate (0.20–0.29), high (0.30–1.00) and very high (>1.00).

RESULTS AND DISCUSSION

The mean squares (Table 3) for the main effects were statistically significant ($p < 0.05$) for days to first flowering and days to 50% flowering, leaf chlorophyll, plant length, leaf length and width, number of nodes/plant, number of branches/plant, number of trifoliate/plant, canopy spread, peduncle length, and internode distance, number of pods/plant, pod length, seed length and seed width, pod wall weight, pod wall thickness, and seed weight. The phenotypic difference among the accessions is predicated on genetic and non-genetic factors (environmental) which is important for the selection of promising accessions for single or multiple characters. The main effect accounted for a larger proportion of the total variation compared to the year effect and genotype-by-year interaction (GYI). Massawe et al. (2005), Misangu et al. (2007), Sesay et al. (2008), Kouassi and Zoro (2009), Chijioke (2010), and Jonah et al. (2010; 2012) reported significant differences ($p \leq 0.05$) among Bambara groundnut accessions evaluated in sub-Saharan Africa based on phenological, morpho-physiological and yield component characters. The phenotypic variation observed for earliness is a pointer to the development of early and medium maturity types through selection and breeding. Earliness (early or medium maturing) must be accompanied by moderate to high seed yield for adoption by farmers. In addition, Jonah et al. (2010 and 2012) noted differences in earliness among the accessions of Bambara groundnut cultivated in the Sudan agro-ecological zone of Nigeria, also considerable variation was observed for all characters, except for pod dry weight and the number of days to maturity.

The year effect significantly ($p < 0.05$) influenced earliness (days to first flowering and 50% flowering), plant length, leaflet length, leaflet width, number of nodes/plant, number of branches/plant, number of trifoliate/plant, canopy spread, pod wall thickness, seed yield/plant, and seed weight. This implies that the mean values for these characters were responsive to differences in precipitation, temperature, sunshine, humidity, and soil factors over years. Insignificant mean squares ($p > 0.05$) were found for genotype-by-year interaction (GEI) for all characters. This suggests that phenotypic response for agronomic and seed yield characters over years was stable and insensitive to differences in climatic and soil factors with high predictability of performance for these characters, and the possibility of developing varieties promising for earliness and high seed yield. These factors could still allow for different results in other locations if these accessions were evaluated for morphological and agronomic characters.

The trend observed for mean values among the accessions for agronomic characters showed the possibility of identifying donor parents for specific or multiple characters. TVSu 12, TVSu 606, and TVSu 586 flowered late (52 d, 51 d, and 50 d, respectively), while TVSu 17, TVSu 277, TVSu 271, and TVSu 278 were earlier (37 d, 38 d, and 39 d, respectively) (Table 4). This suggests a wide scope for selection of donor parents for early, medium, and late maturity groups. Further, TVSu 603, TVSu 589, TVSu 272, TVSu 585, and TVSu 276 had 3 d or 4 d between first flowering and days to 50% flowering compared to TVSu 17. A short interval between days to flower appearance and days to 50% flowering is important for seed set, seed yield, and seed maturity and harvesting plan. The medium maturing accessions are promising to mitigate the early cessation of rainfall during the crop growing season (Hillocks et al. 2012).

The leaf chlorophyll is a precursor for photosynthesis and a determinant of wellness in plants. This was low (35.3) in TVSu 265, followed by TVSu 605 (38.6) but high (56.7) in TVSu 22. The high mean value for leaf chlorophyll content is a pointer to effective photosynthetic activities, usually culminating in dark green leaves and a high number of leaves/plant and leaf biomass. The plant length peaked in TVSu 264. The plant length is important for mechanised crop husbandry including harvesting. TVSu 265 had a long leaflet (8.96 cm) at 10 WAP followed by TVSu 592 (7.52 cm) and TVSu 277 (7.10 cm). The leaflet width spanned 1.56 cm in TVSu 270 to 3.15 cm in TVSu 270. Considering leaflet size (leaflet length and width), TVSu 265, TVSu 262, and TVSu 592 performed best for leaf size (leaf length and width). In contrast, they marked low to moderate values for leaf chlorophyll content. TVSu 14, TVSu 15 and TVSu 605 had high leaf chlorophyll content with moderately long and wide leaves. These accessions are promising as leaf vegetables for fish feed. The canopy cover in Bambara groundnut reduces weed interference in crop growth and development, and frequency of weeding. On the other hand, it creates a favourable environment for disease development. The canopy cover was wide (26.4 cm) in TVSu 585, followed by 25.6 cm in TVSu 588, and 24.40 cm in TVSu 589.

The seed is the sink for photosynthates, seed size (seed length and width) and the number of seeds/pod are important determinants of seed yield. The number of pods/plant was high (86) in TVSu 283 but low (39) in TVSu 17. The moderately long and wide leaflet and moderate leaf chlorophyll content of TVSu 283 enhance the accumulation of photo-assimilates for high flower production and pod number/plant. The number of seeds/plant peaked (at 111) in TVSu 261, followed by 85 seeds in TVSu 267. The top five accessions for seed length are TVSu 17, TVSu 22, TVSu 256, TVSu 261, and TVSu 590, also they had moderate leaf chlorophyll content, medium maturing, high seeds/pod and seed weight while TVSu 590 performed best for seed width (0.92 cm). Four accessions viz. TVSu 283. TVSu 261, TVSu 173, and TVSu 11 outperformed other entries for seed weight/plot. The high seed yield could be due to inherent variation in the genetic makeup, differences in photosynthetic ability, and translocation of dry matter for seed yield. The study showed that TVSu 283 recorded a high pods/plant but low seed weight. This may be associated with few seed sets/pod, competition among reproductive sinks for photo-assimilates, and low accumulation of photosynthates in the seeds. The seed yield recorded in this location is comparable to those reported by other authors in the Sudan agroecology of Nigeria (Jonah et al. 2010 and 2012). Considering multiple characters (earliness and seed yield), the best performing accessions for seed yield are medium maturing. Therefore the development of medium maturity and high seed yielding varieties for

Table 4. Mean separation for some physiological, pod, and seed yield characters among Bambara groundnut accessions evaluated during 2017 and 2018

Accessions	Days to first flowering	Days to 50% flowering	Leaf chlorophyll	Plant height	Leaf length	Leaf width	Leaf petiole length	Trifoliate/ plant	Canopy spread	Peduncle length	Pods/ Plant	Pod width	Seed length	Seed width	Seeds/ plant	Seed weight/
TVSU 12	52a	55a–c	42.9c-i	21.1a-g	6.48b-g	2.25d-n	11.1klm	54d-m	14.4k-m	3.11b-f	17b-g	0.90c-f	0.6b	0.6b-g	69b-f	0.3bcd
TVSU 606	51ab	55a-c	50.4a-d	15.7h	5.52e-h	2.13e-n	13.2e-k	52f-n	13.9i-l	2.26def	10g-p	1.01b-f	0.7b	0.5fg	42c-h	0.24de
TVSU 586	50a-c	54a-e	53.2abc	21.1a-g	6.35b-h	1.97p-i	12.5e-l	53c-j	21.2b	2.3def	4.9op	0.76f	0.6b	0.6b-g	18i	0.09e
TVSU 263	49a-c	55a-c	51.4abc	17.2fgh	6.16b-h	2.35b-m	14.2b-e	73bc	18.9b-e	2.87c-f	14d-l	1.1b-f	1.0b	0.6b-g	72b-e	0.3bcd
TVSU 283	49a-e	55a-c	52.3abc	24.1a	6.77b-g	3.15a-h	16.0ab	50g-l	20.4b-d	4.16b-f	26a	1.1b-f	0.8b	0.6b-g	67b-f	0.3bcd
TVSU 588	49a-e	55a-c	49.8a-e	20.7a-g	5.44e-h	2.53d-h	16.6a	70cde	25.6ab	5.03bc	6k-p	0.75def	0.9b	0.7a-f	32e-f	0.1de
TVSU 592	48a-f	55a-c	39.5e-i	20.1a-h	7.52b	2.92a-d	13.3c-l	63c-g	17.6e-h	3.8b-f	11e-o	1.24b-f	0.8b	0.5d-g	53b-h	0.2cde
TVSU 16	48a-f	54a-e	47.3a-h	19.7a-h	5.50e-h	1.74k-n	12.6c-l	44k-o	17.6e-h	2.25def	16c-h	1.4a-c	0.6b	0.7a-f	53b-h	0.3bcd
TVSU 587	48a-f	57a	47.1a-h	20.3a-h	5.94d-h	2.18d-n	11.3j-l	91a	15.26h-l	2.8cf	13d-n	1.21b-f	0.8b	0.6b-g	26hi	0.1de
TVSU 180	48a-f	54a-e	48.4a-g	19.3b-h	6.37b-h	2.23d-n	14.1b-f	60c-h	16.1f-i	2.89cf	12e-o	1.0b-f	0.8b	0.7a-f	43c-h	0.2cde
TVSU 275	48a-f	56ab	47.8a-h	17.8e-h	5.72e-h	2.18d-n	8.2n	94a	11.4n-q	3.13c-f	14d-l	1.06b-f	0.8b	0.8a-e	38e-i	0.2cde
TVSU 605	48a-f	51f-j	38.6f-i	20.8a-f	6.66b-g	2.63a-g	15.9e-r	49k-o	20.8b	2.48c-f	7i-m	1.2b-f	0.9b	0.7a-g	25hi	0.1de
TVSU 11	48a-h	54a-e	52.4a-c	20.0a-h	6.68b-g	1.83i-n	13.5e-f	40l-o	13.5j-n	2.93c-f	21a-d	1.02b-f	0.8b	0.8a-e	52b-h	0.2cde
TVSU 13	47a-h	52c-f	53.9a-c	19.1b-h	6.82b-g	1.75k-n	12.2e-l	52f-n	9.15qrs	2.70c-f	8i-p	0.9c-f	1.0b	0.6b-g	29f-i	0.1de
TVSU 171	47a-h	55a-c	47.7a-h	20.5a-g	6.34b-h	2.58a-j	13.8a-h	41k-o	15.4h-l	4.4b-e	12e-n	1.32a-e	0.7b	0.6b-g	57c-i	0.2cde
TVSU 282	47a-h	55a-c	44.9b-i	18.4b-h	5.44e-h	2.24d-n	15.7a-d	39m-o	18.2c-f	2.50c-f	5op	0.98b-f	0.8b	0.5e-g	25hi	0.1de
TVSU 178	47a-h	53b-f	49.6a-e	22.1a-e	6.65b-g	2.15e-n	12.0f-l	66c-g	9.0rs	3.2b-f	11.8e-o	0.93c-f	0.9b	0.7a-f	24hi	0.1de
TVSU 173	47a-h	56ab	47.8a-h	20.9a-g	5.94c-h	1.85h-n	11.1klm	51f-n	17.5a-h	2.05def	22abc	1.35a-d	0.8b	0.8a-e	64b-g	0.3bcd
TVSU 264	46a-i	56ab	39.9e-i	24.9abc	6.00c-h	1.69l-n	13.9d-h	56d-m	8.8s	1.83ef	11e-o	1.02b-f	0.9b	0.6a-g	39c-h	0.1de
TVSU 22	46a-i	56ab	56.7a	17.0fgh	5.53e-h	1.96g-n	5.2n	59c-i	15.6g-j	3.92b-f	12o-n	1.18b-f	1.1b	0.7a-f	35d-i	0.1de
TVSU 256	46a-i	53b-f	48.4a-g	22.3a-c	5.89c-h	2.59a-g	12.3e-l	31op	18.8b-e	3.8b-f	13d-n	1.34a-d	1.0b	0.9a	31f-i	0.1de
TVSU 181	45a-i	54a-e	50.0a-c	19.3b-h	5.31gh	2.33d-m	12.6e-l	42k-o	12.9b-p	2.9cf	10g-p	0.99b-f	0.8b	0.6b-g	39c-h	0.2cde
TVSU 174	46a-i	55a-c	49.0a-e	20.3a-h	6.01c-h	2.51a-j	8.9n	40m-o	10.6p-s	1.43f	3.4p	1.8a	0.8b	0.6b-g	27ghi	0.1de
TVSU 591	46a-i	55a-c	50.6a-d	18.7b-h	5.98c-h	2.3d-m	9.8nm	61c-g	16.0f-j	3.52b-f	8i-p	1.0b-f	0.7b	0.4g	18i	0.2cde
TVSU 261	46a-i	52c-f	46.0b-i	20.5a-f	5.59e-h	2.2d-n	11.22k-m	43i-n	18.00d-g	2.62c-f	24ab	1.1b-f	1.1b	0.8a-e	111a	1.7a
TVSU 280	46a-i	56ab	47.7a-h	17.9e-h	5.81e-h	2.36b-m	14.5b-g	65c-g	20.5bc	3.19b-f	11e-o	1.0b-f	0.8b	0.6b-g	35d-i	0.2cde
TVSU 590	44b-l	50i-n	49.6a-e	19.8a-h	5.82c-h	2.3d-m	12.1e-l	41k-o	17.9d-g	4.05d-f	8i-p	1.7a	1.2b	0.9a	30d-i	0.2cde
TVSU 262	44b-l	50i-n	37.5hi	18.7b-h	7.13bc	2.79a-e	12.0f-l	54d-n	14.5j-m	3.4b-f	15c-h	0.9c-f	0.8b	0.6b-g	15i	0.2cde
TVSU 270	44b-l	47l-p	48.3a-g	18.5b-h	5.42fgh	1.56n	11.5i-m	70cd	13.1k-o	2.59b-f	7i-m	1.1b-f	0.8b	0.6b-g	39c-i	0.2cde
TVSU 603	43c-l	46op	48.1a-g	20.4a-g	4.97h	1.78j-n	11.8h-l	43i-o	20.3bcd	4.71b-d	13d-n	1.0b-f	0.6b	0.5fg	47b-h	0.2cde
TVSU 602	43c-l	50in	49.5a-e	20.2a-h	6.78b-g	2.41b-l	11.3j-m	40mno	15.8f-j	2.02def	11e-o	1.0b-f	0.7b	0.6b-g	40c-h	0.2cde
TVSU 589	43c-l	46op	43.7c-i	23.1a-c	6.98b-e	2.34d-f	15.8efg	40mno	24.4a	2.02def	5o-p	1.1b-f	0.89b	0.7a-f	22hi	0.1de
TVSU 272	43c-l	46op	46.6a-i	22.2a-d	6.9b-f	2.2d-n	11.5tu	58c-j	16.0f-j	4.41b-e	12e-o	1.0b-f	0.8b	0.8a-e	20i	0.2cde
TVSU 601	42c-l	52c-f	50.8a-d	22.0a-e	6.34b-h	2.3d-m	15.1h-l	62c-g	9.15grs	4.4b-e	7i-m	0.98b-f	0.8b	0.7a-f	27ghi	0.1de
TVSU 585	42c-l	46op	43.9c-i	20.6a-g	6.09b-h	2.3d-m	15.6a-d	86ab	26.4a	2.94c-f	15c-h	1.52ab	0.8b	0.6b-g	21i	0.1de
TVSU 179	42c-l	50i-n	44.0c-i	19.9a-h	6.21b-h	2.18d-n	13.9j-r	41k-o	10.1q-s	2.12def	5op	0.97b-f	0.6b	0.6b-g	33e-i	0.1de
TVSU 276	42c-l	46op	48.3a-g	20.1a-h	6.63h-g	1.78j-n	19.7cd	58c-j	15.5g-l	3.62b-f	14d-l	1.38a-c	1.0b	0.8abc	16i	0.1de
TVSU 617	42c-l	50i-n	46.3a-i	18.29d-h	6.08b-h	1.68mn	13.5l-p	53d-n	14.1i-m	9.9a	14d-l	0.88c-f	0.71b	0.5d-g	48b-h	0.3bcd
TVSU 268	42c-l	47l-p	48.8a-g	20.6a-g	5.9e-h	2.91a-d	14.7i-o	53d-n	13.5j-n	3.3b-f	12e-o	0.93c-f	0.8b	0.5d-g	54b-h	0.4bc
TVSU 14	41f-l	52c-f	52.4abc	16.87gh	7.0bcd	2.28d-n	15.0i-n	51f-n	10.8o-s	2.84c-f	13d-n	1.0b-f	0.7b	0.6b-g	39c-h	0.1de
TVSU 15	41f-l	46op	55.7ab	20.5a-g	6.9b-f	2.24d-n	12.5p-u	60c-h	18.8b-e	3.12b-f	13d-n	1.0b-f	0.9ab	0.7a-c	75b-d	0.3bcd
TVSU 604	41f-l	45p	52.9abc	23.1ab	5.8c-h	2.7a-j	11.0lm	30op	14.0i-l	3.68b-f	15c-h	1.1b-f	0.9b	0.6b-g	20i	0.1de
TVSU 266	40g-l	56ab	47.4a-h	22.9abc	6.9bcd	2.8a-e	11.9g-l	39mno	15.2h-l	3.72b-f	19d-f	0.81def	0.7b	0.7a-c	57b-h	0.2cde
TVSU 29	40g-l	48k-n	37.8hi	18.0d-h	6.74b-g	3.0ab	13.4e-i	19 p	16.3f-i	2.58c-f	6m-p	0.76f	0.9b	0.5d-g	30f-i	0.1de
TVSU 265	40h-l	51i-n	35.3i	21.9a-e	8.9a	3.0ab	11.2j-m	68c-f	20.0b-e	2.55c-f	10g-p	0.87c-f	0.9b	0.5d-g	42c-h	0.3bcd
TVSU 278	39i-l	50in	43.2c-i	21.1a-g	5.9c-h	2.64a-f	11.9g-l	51f-n	15.1h-l	2.20def	16c-h	1.02b-f	1.1b	0.8abc	70b-f	0.6ab
TVSU 271	39jkl	46op	51.6a-c	22.7a-d	7.0bcd	2.06f-n	12.2e-l	61c-g	19.1b-e	3.91b-f	10g-p	1.1b-f	0.8b	0.6b-g	18i	0.1de
TVSU 277	38kl	47l-p	47.0a-h	22.2a-d	7.1bc	2.5a-g	10.8lm	41l-o	11.2o-r	3.8b-f	14d-l	0.99b-f	0.8b	0.7a-f	26ghi	0.1de
TVSU 17	27l	54a-e	52.0abc	21.7a-f	5.9c-h	2.2d-n	11.1klm	56d-m	15.1h-l	3.0b-f	20a-e	0.78ef	2.1a	0.7a-f	77a-c	0.1de

Table 5. Morphological descriptors of Bambara groundnut selected by STEPDISC procedure

Variable entered	Partial R – square	Pr > F	Wilks' Lambda	Pr < Lambda	Squared Canonical Correlation	Pr > ASCC
Petiole length at flowering	0.89	<.0001	0.11	<.0001	0.02	<.0001
Leaf/plant	0.87	<.0001	0.01	<.0001	0.03	<.0001
Canopy spread	0.78	<.0001	0.002	<.0001	0.05	<.0001
Days to 50 % flowering	0.71	<.0001	0.0003	<.0001	0.07	<.0001
Peduncle length	0.63	<.0001	0.0003	<.0001	0.08	<.0001
Number of pods/plant	0.54	<.0001	0.0003	<.0001	0.09	<.0001
Leaflet length at 10 WAP	0.42	<.0001	0.0001	<.0001	0.10	<.0001
Trifoliate/plant	0.42	<.0001	0.0008	<.0001	0.11	<.0001
Internode distance	0.42	<.0001	0.0005	<.0001	0.12	<.0001
Leaflet width at 10 WAP	0.44	<.0001	0.0003	<.0001	0.13	<.0001
Seed weight/plot	0.43	<.0001	0.001	<.0001	0.13	<.0001
Pod length	0.42	<.0001	0.05	<.0001	0.14	<.0001
Pod wall weight	0.40	<.0001	0.002	<.0001	0.15	<.0001
Pod width	0.43	<.0001	0.001	<.0001	0.15	<.0001
Leaf chlorophyll	0.37	<.0001	0.001	<.0001	0.16	<.0001
Root length	0.36	<.0001	0.0008	<.0001	0.16	<.0001
Seed width	0.34	<.0001	0.005	<.0001	0.17	<.0001
Seed length	0.32	<.0001	0.003	<.0001	0.17	<.0001
Leaflet length at flowering	0.33	<.0001	0.0005	<.0001	0.08	<.0001
Seed/plant	0.33	<.0001	0.0007	<.0001	0.18	<.0001
Plant length	0.33	<.0001	0.0007	<.0001	0.18	<.0001
Number of nodes/stem	0.24	<.0001	0.0008	<.0001	0.19	<.0001
Leaflet width at flowering	0.24	<.0001	0.0006	<.0001	0.20	<.0001
Days to first flowering	0.23	<.0001	0.0005	<.0001	0.21	<.0001

the humid agroecological zone was feasible. TVSu 261 had 46 d to anthesis, moderately high leaf chlorophyll, pods/plant, and high seed weight/plot is promising for this agroecology that is characterised by early cessation of rainfall and absence of irrigation.

The stepwise discriminatory model picked independent variables for entry into the analysis based on their discriminatory power. A variable is considered for selection, only if its partial multivariate F ratio is greater in magnitude than a specified value. The stepwise discriminant analysis showed significant responses by the 24 characters for partial R^2, Wilks, and canonical correlation (Table 5). Three redundant characters (pod wall thickness, branches/plant, and petal length) were found among the characters examined. The morphological, reproductive, pod, and seed yield characters showed significant contribution to the variability observed among the accessions. These characters recorded significantly high discriminating ability among the Bambara groundnut accessions, and concentrating on these characters will reduce the time and cost, and effectively discern accessions in this species. The phenotypic variation found among the accessions is predicated upon the inherent variation.

The principal component analysis was used to determine the relative contribution of 24 morphological and agronomic characters to total variability. The PCA showed that five out of the 24 PC axes had eigenvalues greater than 2.00, and altogether explained 53 % of the total variance (Table 6). The eigenvalues for the first five PC axes were 4.45, 3.54, 2.60, 2.70, and 2.00. The PC axes 1 and 2 had eigenvalues greater than 3.00 and explained 29 % of the total variation. The relative discriminating ability of the eigenvalues was high in PC axis 1 (4.45) and 2 (3.54), they accounted for 29 % of the total variance. The first PC axis was responsible for 19 % of the total variation and was positively correlated with petiole length at 50 % flowering, leaf width at 10 WAP, leaves/plant at 10 WAP, plant length at 10 WAP, canopy spread at 10 WAP and leaflet width at 10 WAP with moderate and positive coefficients on PC 1. The seed weight showed positive and significant correlation coefficient with plant canopy (0.27*), number of trifoliate (0.22*), leaves/plant (0.30), leaf length (0.28*), leaf width (0.35*), seeds/plant (0.11*), leaf petiole length (0.15*),

Table 6. Eigenvalue and vectors from the first five principal component axes for 27 characters among Bambara groundnut accessions from Nigeria

Characters	Prin 1	Prin 2	Prin 3	Prin 4	Prin 5
Days to first flowering	–0.09	0.09	0.46	–0.09	0.04
Days to 50% flowering	–0.08	0.15	0.38	–0.08	0.34
Leaf chlorophyll	–0.16	0.13	–0.02	0.35	–0.12
Plant length at 10 WAP	0.25	–0.11	–0.12	0.10	0.28
Leaf length at 10 WAP	0.22	–0.23	0.05	–0.04	0.27
Leaf width at 10 WAP	0.31	–0.23	–0.05	0.05	0.01
Petiole length at flowering	0.32	–0.20	0.10	–0.27	0.02
Number of nodes/stem	0.10	0.05	–0.11	–0.13	–0.49
Leaflet length at flowering	0.20	–0.17	–0.17	–0.28	0.04
Leaflet width at flowering	0.24	–0.09	–0.06	–0.31	0.09
Number of leaf/plant	0.26	0.01	0.34	0.09	–0.15
Number of trifoliate/plant	0.21	0.10	0.35	0.06	–0.11
Canopy spread	0.25	–0.11	0.27	0.11	–0.21
Peduncle length	0.12	–0.19	–0.03	0.34	–0.12
Internode distance	0.09	–0.23	–0.06	0.26	0.17
Number of pods/plant	0.17	0.37	–0.11	–0.02	0.15
Root length	–0.01	–0.003	–0.004	0.009	0.42
Pod length	0.20	–0.04	–0.09	0.22	–0.16
Pod width	0.07	–0.04	0.23	0.26	0.08
Seed length	–0.01	0.11	–0.12	0.15	0.20
Seed width	0.12	0.09	0.01	0.40	0.14
Pod wall weight	0.18	0.34	–0.06	0.09	–0.11
Number of seeds/plant	0.17	0.43	–0.05	0.004	–0.04
Seed weight/plot	0.20	0.40	–0.09	0.006	0.11
Eigenvalue	4.45	3.54	2.60	2.27	2.00
Difference	0.91	0.94	0.33	0.26	0.45
Proportion	0.16	0.13	0.09	0.08	0.07
Cumulative (%)	19	29	38	46	53

nodes/stem (0.18*). These morphological markers are efficient for characterisation and conservation. In previous findings, Olukolu et al. (2012) noted the high discriminatory ability of plant length, number of trifoliate/plant, and pods/plant, whereas Touré et al. (2012) and Molosiwa (2012) noted differences among Bambara groundnut accessions for days to first flowering, plant length, pod number, canopy spread and leaf area. The highest negative coefficient was found in leaf chlorophyll content. The first PC axis demonstrated an inverse relationship among phenological, morphological, and seed yield characters. This indicates competition for photo-assimilates between phenological, morphological, and seed yield characters among early maturing accessions, hence poor seed yielders. The second PC axis explained an additional 13% of the total variation and showed moderately high coefficients and high discriminatory power of pod and seed yield characters, and a high frequency of positive coefficients than negative coefficients. The coefficients of seeds/plant, seed weight/plot, pods/plant, pod wall weight, and the number of pods/plant were low on PC axis 1, but moderately high on PC axis 2. Moderate and positive coefficients on the PC axis may be associated with phenotypic variability in the germplasm. Morphological characters recorded positive coefficients on PC axis 1, but with negative coefficients on PC axis 2. The second PC axis depicts equal loading for leaflet length, leaflet width, and internode distance. The preponderance of morphological characters on PC axis 1 and pod and seed yield characters to PC 2 is similar to the findings reported by Molosiwa (2012) among the Bambara germplasm collection in Botswana. Characters with negative coefficients on PC1 had positive coefficients on PC 2 and vice versa whereas other characters marked positive or negative coefficients on both PC 1 and 2. The third PC axis explained 9% of the total variability and showed a high discriminatory ability of phenological characters (days to first flowering and days to 50% flowering). The axis showed an inverse

Table 7. Cluster means for phenological, agronomic, pod, and seed yield characters in Bambara groundnut in Nigeria

	Characters																									
Cluster	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
1	47	51	50.23	22.31	6.64	2.27	13.92	20.00	3.33	5.87	2.47	247	72	20.39	4.44	1.21	20	8.45	1.48	1.12	0.76	0.56	6.86	0.15	57	0.31
2	47	53	47.36	20.54	6.47	2.00	12.96	14.90	2.86	6.33	2.37	207	56	19.07	3.85	1.41	10	6.99	1.41	1.05	0.90	0.76	3.95	0.12	23	0.15
3	45	52	47.28	18.86	6.01	1.92	12.75	13.22	2.61	6.29	2.38	73	30	12.82	2.71	1.26	8	7.42	1.53	0.88	0.91	0.61	5.84	0.13	33	0.17
4	48	53	48.56	19.63	6.04	1.93	12.72	15.18	2.83	6.10	2.15	154	56	15.25	2.72	1.08	16	8.39	1.54	1.11	0.79	0.66	10.27	0.21	61	0.30
5	42	51	45.40	21.11	6.35	2.12	11.76	19.14	2.80	7.07	2.62	203	61	17.36	3.33	1.25	15	6.77	1.61	1.00	0.16	0.68	7.57	0.14	63	0.37
6	46	53	43.68	20.38	6.15	2.17	15.24	15.97	2.27	6.37	2.41	272	90	21.13	2.49	1.22	9	6.06	1.56	1.24	0.86	0.68	9.36	0.17	30	0.17
7	47	56	39.95	22.91	6.75	2.03	13.94	12.10	2.83	6.00	1.69	127	51	8.80	1.83	1.71	12	44.63	1.40	1.02	0.97	0.65	4.00	0.13	39	0.13
8	45	55	45.42	20.57	6.33	1.95	11.22	18.54	3.00	5.59	2.20	202	61	18.00	2.62	1.20	24	6.90	1.49	1.17	1.11	0.86	21.76	0.16	111	0.70
9	45	52	49.91	20.21	6.20	2.03	11.88	14.25	3.16	6.17	2.23	172	53	16.18	4	1.44	10	6.54	1.62	1.19	0.90	0.69	4.92	0.18	27	0.17
10	43	51	47.95	20.31	6.32	2.05	12.06	14.72	2.42	6.33	2.31	115	43	13.73	3	1.24	11	6.69	1.49	1.07	0.82	0.67	6.58	0.16	34	0.19

1 = Days to first flowering, 2 = plant height at 50 % flowering, 3 = Chlorophyll, 4 = plant length, 5 = Leaf length, 6 = leaf width, 7 = Petiole length, 8=Petal length, 9=Branches/plant, 10 = leaflet length, 11 = Leaflet width, 12 = Leaves/plant, 13 = trifoliate/plant, 14=Plant spread, 15 = nodes/plant, 16 = pod length, 17 = Internode distance, 18 = Pods/plant, 19 = Root length, 20 = Pod length, 21=pod width, 22 = Seed length, 23 = Seed width, 24 = Pod wall weight, 25 = Pod wall thickness, 26 = Seeds/plant, 27 = Seed weight.

Table 8. Clustering summary for 50 accessions of Bambara groundnut (*Vigna subterranea* [L.] Verdc) accessions from Nigeria

Cluster	Frequency	Maximum distance from accessions	Nearest cluster	Distance from the cluster centroid
1	2	20.14	6	48.57
2	5	23.19	9	35.34
3	3	18.72	10	44.32
4	8	26.32	9	40.22
5	5	27.32	2	42.24
6	3	17.27	1	43.57
7	1	0	10	42.65
8	1	0	5	51.14
9	9	28.17	2	35.34
10	13	26.39	7	42.65

relationship between earliness and morphological characters. The study indicates that the first five PC axes contributed half of the total variance. Therefore, a few PCs will be required to explain the total variance in the germplasm. This suggests a moderately high level of phenotypic variability in the germplasm. However, there is a high level of variability associated with characters that correlated positively on PC 1, 2, 3, and 4. The trait loading across the five PCs is an indication of pleiotropic gene effects, which clearly explains gene linkage in trait expression.

Clusters 4, 9, and 10 had a large number of accessions with a high level of phenotypic diversity. Accessions in these clusters may be utilised as donor parents for single or multiple characters for hybridisation and conservation. The cluster means (Table 7) showed that Bambara groundnut accessions grouped in cluster 5 are earlier, and members in cluster 1 performed best for leaf chlorophyll content. Accessions in clusters 1 and 9 had more branches/plant compared to other clusters. The number of trifoliate/plant peaked in cluster 6 while accessions grouped in cluster 8 outperformed other entries for seed length, seed width, seeds/plant, and seed weight. This implies that accessions in cluster 6 are donor parents for seed metric and seed yield characters. Hybridisation among members of clusters 8, 5, 6, and 3 in a diallel fashion may recombine the genes and throw up segregating population upon which selection of photosynthetically efficient, high pod number and seed yield varieties for the rain forest agroecology. The PROC FASTCLUST procedure grouped the Bambara groundnut accessions into 10 clusters. The number of accessions per cluster ranged from 1 to 13 (Table 8). The distance between the cluster centroid was minimum in clusters 2 and 9 and maximum in cluster 8. The maximum distance between accessions was recorded in

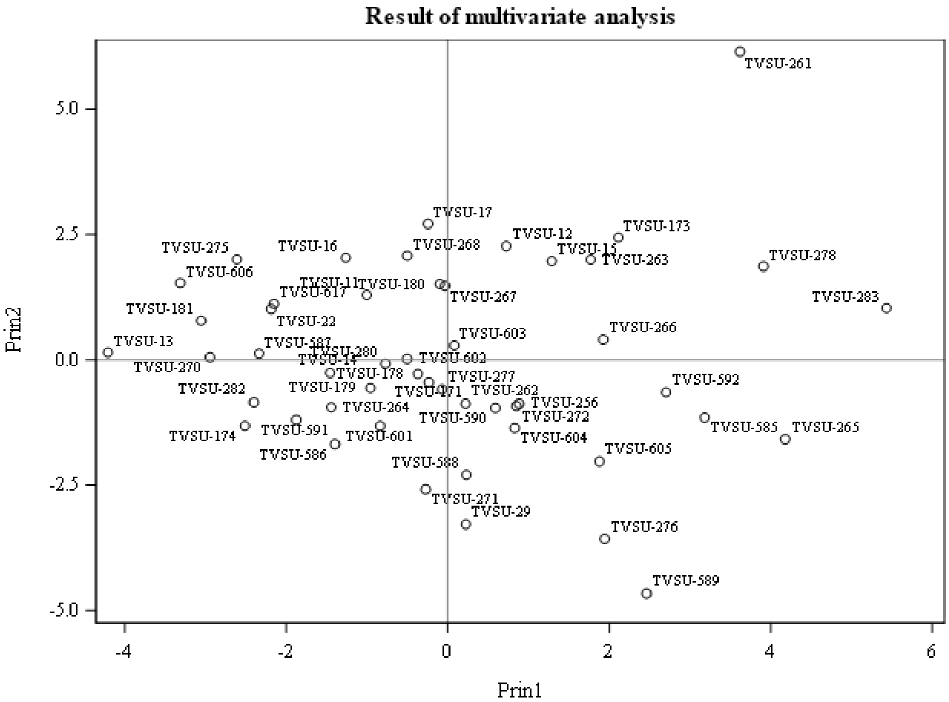

Figure 1a. Dispersion of 50 accessions of Bambara groundnut on PC axis 1 and 2

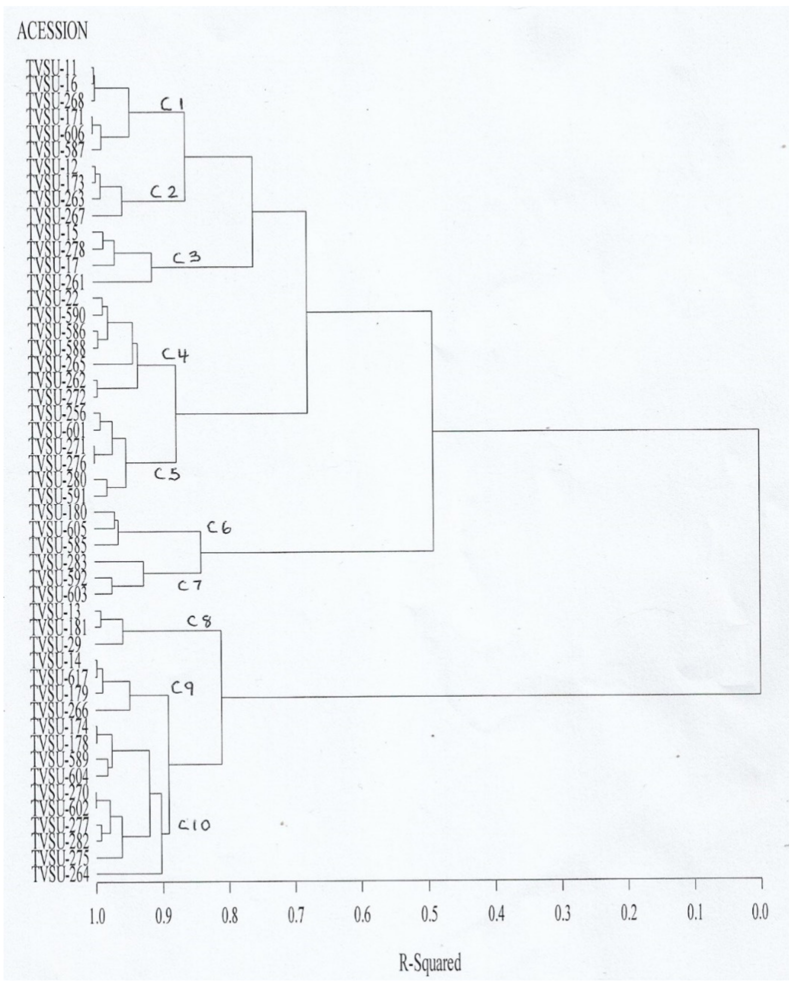

Figure 1b. Dendrogram constructed for 50 accessions based on phenological, morpho-physiological, seed yield and yield component traits.

Table 9. Direct and indirect effects of eighteen causal variables on seed yield of fifty accessions of Bambara groundnut

Characters	Seed /plant	Days to 50% flowering	Leaf Chlorophyll content	Petal length	Petiole length	Leaf length	Leaf width	Leaves /plant	Trifoliate /plant	Canopy spread	Peduncle length	Internode distance	Pods /plant	Root length	Pod length	Pod width	Seed length	Seed width
Direct on Seed weight	0.61	–0.06	–0.02	0.02	0.06	0.004	–0.005	–0.01	0.05	–0.03	–0.004	0.04	0.08	–0.06	0.03	0.02	–0.03	0.021
Indirect via Seed/plant		–0.001	–0.001	0.004	0.007	0.000	0.000	–0.001	0.008	–0.002	0.000	0.004	0.037	–0.007	0.004	–0.001	0.000	0.003
Indirect via Days to 50F% flowering	0.02		0.000	–0.003	0.004	0.000	0.000	–0.001	0.006	0.003	0.001	–0.006	0.005	–0.004	–0.003	0.000	–0.001	0.000
Indirect via Chlorophyll	0.02	0.001		–0.001	–0.013	0.000	0.001	0.000	–0.004	0.001	0.000	0.002	0.004	–0.005	0.003	0.001	–0.002	0.002
Indirect via Petal length	0.09	0.007	0.001		0.010	0.001	–0.001	–0.002	0.008	–0.005	0.000	0.005	0.013	–0.003	–0.001	0.000	–0.001	0.005
Indirect via Petiole length	0.07	–0.004	0.004	0.004		0.001	–0.002	–0.004	0.012	–0.009	0.000	–0.001	0.010	0.003	0.001	0.001	0.002	0.002
Indirect via Leaf length	–0.01	0.005	0.002	0.005	0.018		–0.001	–0.001	0.002	–0.001	0.000	–0.002	0.000	0.001	0.001	–0.001	0.003	–0.002
Indirect via Leaf width	0.03	0.000	0.002	0.004	0.022	0.001		–0.002	0.004	–0.007	0.000	0.004	0.003	0.005	0.004	–0.001	0.001	0.001
Indirect via Leaves/plant	0.06	–0.002	0.000	0.004	0.019	0.000	–0.001		0.037	–0.017	0.000	0.002	0.007	0.003	0.002	0.002	–0.002	0.002
Indirect via Trifoliate/ plant	0.10	–0.006	0.002	0.004	0.014	0.000	0.000	–0.009		–0.011	0.000	0.003	0.008	0.004	0.002	0.003	0.001	0.002
Indirect via canopy spread	0.03	0.006	0.001	0.003	0.018	0.000	–0.001	–0.007	0.018		0.000	0.007	–0.007	0.005	0.005	0.002	0.001	0.003
Indirect via Peduncle length	–0.04	0.009	–0.002	0.001	0.002	0.000	0.000	–0.001	0.005	–0.004		0.008	–0.003	0.003	0.003	0.001	0.000	0.002
Indirect via Internode distance	0.06	0.007	–0.001	0.003	–0.002	0.000	0.000	–0.001	0.004	–0.005	–0.001		–0.001	–0.011	–0.001	–0.001	0.000	0.002
Indirect via Pods/plant	0.23	–0.003	–0.001	0.004	0.008	0.000	0.000	–0.001	0.005	0.003	0.000	0.000		–0.004	0.002	0.000	–0.002	0.002
Indirect via Root length	0.07	–0.004	–0.002	0.001	–0.003	0.000	0.000	0.001	–0.003	0.003	0.000	0.008	0.005		0.003	0.000	0.001	0.001
Indirect via Pod length	0.07	0.006	–0.002	–0.001	0.003	0.000	–0.001	–0.001	0.003	–0.005	0.000	–0.001	0.006	–0.005		0.004	0.003	0.004
Indirect via Pod width	–0.03	–0.001	–0.001	–0.001	0.004	0.000	0.000	–0.001	0.010	–0.004	0.000	–0.003	–0.003	0.001	0.008		0.003	0.006
Indirect via Seed length	0.006	–0.003	–0.002	0.001	–0.005	0.000	0.000	–0.001	–0.002	0.001	0.000	0.000	0.005	0.001	–0.004	–0.002		–0.002
Indirect via Seed width	0.08	0.001	–0.00	0.05	0.05	0.000	0.000	–0.001	0.006	–0.004	0.000	0.003	0.010	–0.003	0.006	0.005	0.003	
Total	1.51	–0.04	–0.02	0.69	0.17	0.006	–0.01	–0.05	0.17	–0.09	–0.007	0.008	0.18	–0.075	0.07	0.03	–0.02	0.05

cluster 9. The distance from the cluster centroid range from 35.34 to 51.14. This is related to the high level of phenotypic diversity among the accessions in each cluster. The 10th cluster had sub-clusters structured by phenotypic characters. However, closely related accessions per cluster were frequently encountered, and few phenotypic duplicates were found.

The 2-dimensional plot of principal component axes 1 and 2 displayed the projections of 50 accessions of Bambara groundnut (Figure 1a) into 4 quadrants alongside the characters responsible. The pattern of variation showed by the PC axis was consistent with the correlation coefficients for pairwise association between characters. The biplot and PC analysis demonstrated that characters that contributed the most to the first PC axis were negatively associated with major characters of the second PC. The first quadrant (Q1) was occupied by ten accessions. The dispersion of accessions in this quadrant showed high variability for the number of leaf trifoliate/plant, the number of seeds/plant, and seed weight/plot. TVSU 261 was widely separated from other accessions but dispersed close to the upper right-hand corner of quadrant 1 with the moderate and positive coefficient on PC 1 and 2. The second quadrant was occupied by thirteen accessions with positive and negative coefficients on PC axes 1 and 2, respectively. This axis demonstrated the high discriminatory ability of plant length at 10 WAP, leaflet width at 10 WAP, leaflet length at 10 WAP, pod length, and canopy spread. In the second quadrant, no accession was dispersed in the upper left-hand corner with low correlation coefficients on PC 2, but high loading on PC 1. Fifteen accessions were ordered into the third quadrant, with moderate and negative coefficients on PC 1 and 2. Dispersion of accessions in this quadrant is consistent with the discriminatory power of root length with negative coefficients on PC axes 1 and 2. Further, twelve accessions were dispersed in the fourth quadrant, they demonstrated high discriminatory ability for earliness (days to first flowering and 50% flowering), leaf chlorophyll, and pod wall thickness. The pattern of genetic variation inherent in the accessions could allow for the selection of donor parents and inter-cluster hybridisation for the introgression of characters within clusters and among clusters. Hybridisation between accessions dispersed in quadrants 1 and 4 may evolve a new population with varying periods of maturity. In addition, crosses between accessions dispersed in quadrants 1 and 2 may provide varieties with improved seed yield and biomass. The graphical representation showed an overlap of phenotypic characters and phenotypic duplicates.

The dendrogram grouped the 50 accessions into ten clusters at 88% level of similarity. Six accessions starting from TVSU 11, 16 and 268 into a sub-cluster, and TVSu 171, 606, and 587 into the second sub-cluster in cluster 1 (Fig. 1b). Members of this cluster are characterised by a low number of leaf trifoliate/plant, few pods/plant, and low seed yields. The second cluster comprised four accessions namely TVSU 12, 173, 263, and 267. Four accessions (TVSu 15, TVSu 278, TVSu 17, and TVSu 261) were grouped into cluster 3, they performed best for seed length and width, seed weight, the number of seeds/plant, and pod wall weight. The accessions ordered into cluster 4 had a long leaflet, while members of cluster 6 (TVSU 180, TVSU 605, and TVSU 585) had a high number of leaf trifoliate/plant and are an important vegetable component for fish feed. In contrast, TVSU 13, TVSU 181, and TVSU 29 in cluster 9 recorded a low number of trifoliate/plant and narrow leaflet widths. Ten accessions were ordered into cluster 10 (starting from TVSU 174 to TVSU 264), cluster members had long leaflets compared to other clusters. TVSu 174 and TVSu 178, TVSu 270, and TVSu 602 are phenotypically related. This is similar to phenotypic duplicates recorded on the PC plot of axis 1 by 2.

Seed weight is associated with improved translocation of assimilates to be stored in the seed, this is under polygenic action and shows interdependence among agronomic, seed metric, and seed yield component characters. The direct and indirect effect of independent characters on seed yield (Table 9) shows that the number of seeds/plant had the largest direct effect on seed yield (kg), followed by the number of pods/plant, petiole length, number of trifoliate/plant, number of nodes/plant and pod length and pod width. These characters are directly related to seed weight. The number of seeds/plant is an index for improvement in seed yield. Phenotypic improvement in favour of the number of seeds/plant will enhance seed yield. Karikari and Tohama (2004), Makanda et al. (2009) and Jonah et al. (2012) reported a positive and significant association between seed weight and the number of seeds/plant, and a positive direct effect of high seeds/plant and seed yield in Bambara groundnut. In another study, Fatimah et al. (2021) identified leaf length and width, and fresh stover weight to be highly effective in the selection of high yielding genotype of Bambara groundnut in Indonesia. The number of days to 50% flowering recorded the largest negative direct effect on seed yield. This infers the possibility of having high seed-yielding with medium maturity genotypes for the rainforest agroecological zone. The direct path of seeds/plant was masked by an indirect effect of peduncle length, pod width, and leaf length. This may be associated with assimilate partitioning and competition for photosynthate between morphological (leaflet length and peduncle length) and reproductive sinks (seed/pod) during the reproductive phase. On the contrary, Misangu et al. (2007) found a positive and significant correlation between seed yield and leaf length among Bambara groundnut accessions evaluated in Tanzania. The pod length had a positive direct effect on seed yield, though with a low coefficient. In agreement with our result, Jonah et al. (2012) concluded a positive contribution of pod length to seed yield among Bambara groundnut accessions evaluated in the northeast, Nigeria. This explains that improvement in morpho-physiological and seed metric characters will scale up seed yield. In addition, the direct path of seeds/plant was masked by leaf length and pod width. This shows that accessions with short leaflet lengths are photosynthetically less efficient with high competition for photo-assimilates for seed weight and pod width. The positive contribution of many pods on an individual plant basis to seed yield was masked by canopy spread, peduncle length, and pod width. The foregoing is similar to the inverse relationship observed between these characters and competition for photo-assimilates between seed organs and morphological characters. The path analysis emphasised that the negative effect of days to 50% flowering on seed yield was largely due to an indirect effect of petiole length, number of trifoliate/plant, number of pods/plant, root length, pod width, and seed width.

CONCLUSION AND RECOMMENDATIONS

Bambara groundnut accessions demonstrated large phenotypic variability and high discriminatory ability of leaflet length and width at 10 WAP, canopy spread, and leaf/plant, seeds/plant, and seed weight. These morphological markers are efficient for morphological characterisation and conservation. The pod wall thickness, branches/plant and petal length with low variability are not important characters for consideration during characterisation. Accessions in cluster 6 are donor parents for seed metric and seed yield characters. The magnitude of phenotypic variation varies among and within accession, this is useful to breeders and potential users of Bambara groundnut. TVSu 17, TVSu 277, TVSu 271, and TVSu 278 are phenotypically distinct accessions for earliness. Phenotypic improvement in pods/plant, petiole length, and petal length will enhance seed weight. The masking action of leaf length, peduncle length and pod width was evidence of competition for assimilates between reproductive and morphological characters. Hybridisation among best-performing accessions for specific characters will evolve new varieties with medium maturity and seed yield through selection. TVSu 261 is a donor parent for seed weight and TVSu 283 for pods/plant. They are recommended for further evaluation and commercialisation in the rain forest agro-ecology

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CONFLICT OF INTEREST

The authors declared no conflicts of interest with respect to research, authorship and publication of this article.

ETHICAL COMPLIANCE

The authors have followed the ethical standards in conducting the research and preparing the manuscript.

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1. Adeniji, O. T. Conceptualize this research, set out the field research, monitored field data collection, and report writing.
2. Olosunde, Busayo undergraduate research student, collected data during 2017 cropping season and report writing.
3. Ekanem, Ukobong analysed the raw data.
4. Adekoya, Modinat monitored the research during 2018 cropping season and report writing.
5. Iseghohi, Innocent monitored the research during 2017 cropping season.
6. Badmus, Adenike monitored the research during 2018 cropping seasons and report writing.