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Selection criteria and yield stability in a large collection of African yam bean [*Sphenostylis stenocarpa* (Hochst ex. A. Rich) Harms] accessions

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Research Article

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Abstract

African yam bean (AYB) is an underutilized legume with significant potential for food security in sub-Saharan Africa, yet limited research exists on optimizing its seed yield through selective breeding. In this study, the seed yield (SY) performance and relative importance of some yield-related traits on SY in AYB were assessed. One hundred and ninety-six accessions of AYB were evaluated for 2 years in three agro-ecologies of Nigeria. The experimental design was a 14 × 14 lattice design with three replicates. Data were recorded on SY and 13 SY-related traits. Positive significant genotypic correlations were found between SY and 11 of these traits. Pod length (PL) had a negative significant relationship ($r_g = -0.44^{**}$) with SY. Path coefficient analysis identified days to maturity (DM), pod weight (PW), shelling percentage (SP), number of seeds per pod (NSPD), 100-seed weight (HSW) and seed thickness (ST) as traits with positive direct effects on SY. The additive main effect and multiplicative interaction analysis revealed highly significant accession, environment, accession × environment interaction and interaction principal components effects for SY. Accessions TSs-119, TSs-101, 138A, TSs-4, TSs-157A and TSs-61 were identified as superior and stable, and should be considered for further breeding purposes. Selection criteria for improved SY in AYB should include DM, PW, SP, NSPD, HSW and ST. The identified stable, high-yielding accessions and key yield-related traits provide a framework for accelerating AYB improvement across diverse agro-ecologies.

Introduction

Access to cheap energy-protein sources by people experiencing poverty in sub-Saharan Africa is limited by the much emphasis devoted to major staple food crops to the detriment of indigenous underutilized leguminous crops (Aremu *et al*., 2019). In recent times, genetic improvement of indigenous legumes such as African yam bean (AYB) [*Sphenostylis stenocarpa* (Hochst ex. A. Rich) Harms] is gaining popularity in Africa. The focus on AYB is not only for its nutritional values, but also for its socio-cultural significance (Ojuederie *et al*., 2015), adaptive nature to wide climatic and soil conditions (Aremu *et al*., 2020), nitrogen-fixing ability which makes it useful in land reclamation (Assefa and Kleiner, 1997; Oganale, 2009), medicinal properties (Potter, 1992) and its inherent lectin which is useful against storage pests (Omitogun *et al*., 1999). However, due to some non-appealing characteristics, lack of exchangeable planting seeds and non-availability of improved cultivars, the few available accessions are left in the hands of indigenous farmers (Klu *et al*., 2001). Although several reports have revealed considerable variation in yield and yield-associated traits among AYB accessions, no improved variety has been released. The current average yield reported for AYB range from 200 to 550 kg/ha (Aremu *et al*., 2020).

Yield is a quantitative trait with quite low heritability, and it is the product of several interacting component traits that are highly subjective to environmental influences (Zhao *et al*., 2016). Yield improvement in crops is associated with the optimization and selection of heritable yield components (Olomitutu *et al*., 2022a). Selecting any heritable component trait(s) involves a complex pathway that leads to the formation of the complex (quantitative) trait (Nwofia *et al*., 2013; Kang, 2015). Correlation coefficients help to measure the level of interrelationship existing between paired traits. It is very effective in determining yield contributing characters and in indirect selection (Kumar *et al*., 2015; Sesay *et al*., 2017). However, the use of correlation coefficients alone is not always adequate, as it provides only one-dimensional information without considering the interrelationships among all yield component traits (Nwofia *et al*., 2013; Kang, 2015). Path coefficient analysis is a standardized regression statistical technique that untangles correlation coefficients into direct and indirect effects in such a way that the contribution of each causal character to yield is known. It estimates the direct effect of a component trait on yield, and its indirect effects through another predictor component traits and helps in partitioning the traits into order of importance for selection and improvement purposes (Dewey and Lu, 1959; Cramer and Wehner, 2000; Nwofia *et al*., 2013; Kang, 2015; Kumar *et al*., 2015; Sesay *et al*., 2017). Kumar *et al*. (2015) suggested that combining correlation with path coefficient analyses provides a better appreciation of the causal relationship between pairs of characters. Previous studies in AYB by Nwofia *et al*. (2013) and Aremu *et al*. (2019) have shown that yield is high corrected with and directly influenced by seeds per pod, pod filling time, pod length and pods per plant.

Though correlation and path coefficient analysis are still very useful in identifying these key yield component traits, the inconsistencies in the performance of the same genotype in many environments for specific traits make prediction of their phenotypic performance across a wide environment difficult (Perkins and Jinks, 1968). Hence, there is a need to evaluate the crop varieties' stability across contrasting environments to facilitate the selection of high-yielding and consistently performing varieties (Ariyo, 1990). Several stability statistics are used in partitioning genotype × environment interaction. The additive main effect and multiplicative interaction (AMMI) method (Gauch, 1992) is one of the most frequently used. The AMMI method combines analysis of variance for genotype and environment main effects with the principal component analysis of the genotype × environment interaction into one (Zobel *et al*., 1988). Because the AMMI model does not provide a specific stability measure, AMMI stability value (ASV) was proposed by Purchase (1997) to rank genotypes according to their yield stability value. The ASV is estimated using interaction principal component axes (IPCA) 1 and 2. Genotypes with the least ASV are considered stable or adapted (Purchase, 1997). However, the idea that the most stable genotypes would not necessarily give the best yield performance has necessitated approaches incorporating both mean yield and stability in a single index, hence the yield stability index (YSI) (Bose *et al*., 2014). The identified stable, high-yielding AYB genotypes can serve as valuable parents to develop improved varieties with enhanced yield stability. This study was conducted to (i) investigate inter-relationship and relative importance of some yield-related traits on seed yield of 196 AYB accessions and (ii) assess seed yield performance of AYB accessions evaluated in six environments.

Materials and methods

Experimental materials, research sites and experimental design

The experimental materials, research sites, experimental design, site management practices and data collection are as described by Olomitutu *et al*. (2022a, 2022b). Briefly, the genetic materials comprised 196 accessions of AYB, obtained from the Genetic Resource Center, International Institute of Tropical Agriculture (GRC-IITA), Ibadan. The field experiments were conducted over a 2-year period at Ibadan, Kano and Ubiaja. At each location, a 14 × 14 lattice design with three replicates was employed. The plots were single rows measuring 4.0 m in length and spaced 0.75 m. Seeds were sown 0.5 m apart within the rows, resulting in a plant population density of 26,666 per hectare. Staking was done 3 weeks after sowing. Weeds were controlled manually. Phosphorus fertilizer application in the form of triple superphosphate at a rate of 50 kg P/ha and staking were performed 3 weeks after planting. Fortnightly, Cypermethrin 30 g/l + Dimethoate 250 g/l EC and Macozeb 80% WP were applied at the rate of 200 ml and 200 g per 20 l of water, respectively, from the inception of flowering to harvest maturity, to control floral and pod pests, and fungal diseases. Ibadan and Kano were irrigated, while Ubiaja was rainfed. Manual weeding was carried out when necessary to keep the field clean.

Data collection

Data were collected on days to flowering, days to maturity (DM), pod filling time (PFT), number of pod/plant (NPPL), pod weight (PW, g/plant), pod length (PL, cm), number of locules/pod (NLPD), number of seeds/pod (NSPD), shelling percentage (SP), 100-seed weight (HSW, g), seed yield (SY, g/plant), seed length (SL, mm), seed width (SW, mm) and seed thickness (ST, mm) using the IITA descriptors for AYB (Adewale and Dumet, 2011).

Data analyses

Trait associations

To determine the inherent relationships between paired traits, genotypic (r_g) correlation coefficients were estimated using META-R (Multi Environment Trail Analysis with R for Windows) version 6.04 (Alvarado *et al*., 2015). Path coefficient analysis based on genotypic correlation was performed to determine each trait's direct and indirect effects on seed yield according to the procedure described by Kang (2015).

AMMI analysis

Plot mean of seed yield/plant (SYPL) in each of the six year × location environments was subjected to AMMI analysis using GEA-R (Genotype × Environment Analysis with R for Windows) Version 4.1 (Pacheco *et al*., 2015). The AMMI model is given as follows:

$$Y_{ij} = \mu + G_i + E_j + \sum\nolimits_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + e_{ij}$$

where; Y_{ij} = mean of yield of ith accessions in the jth environment; μ = grand mean; G_i = the ith accession mean deviation; E_j = the jth environment mean deviation; λ_k = square root of the eigenvalue of the PCA axis k; α_{ik} and γ_{jk} = the ith accession and jth environment PCA scores; e_{ij} = residual.

AMMI stability value (ASV)

The ASV was estimated following the formula proposed by Purchase (1997) as follows:

$$\mathrm{ASV} = \sqrt{\left[\frac{\mathrm{SS_{IPCA1}}}{\mathrm{SS_{IPCA2}}}\left(\mathrm{IPCA1_{score}}\right)\right]^2 + \left(\mathrm{IPCA2_{score}}\right)^2}$$

where; SSIPCA1 = sum of squares of interaction principal component analysis 1; SSIPCA2 = sum of squares of interaction principal component analysis 2; IPCA1 and IPCA2 = interaction principal component analysis one and two. The smaller the ASV value (negative or positive), the more stable the accession across environments (Purchase, 1997).

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Yield stability index (YSI)

The YSI was calculated based on the rank of the mean seed yield of accessions across the six environments and the rank of ASV.

$$\mathrm{YSI} = \mathrm{RASV} + \mathrm{RSY}$$

where; RASV = rank of the accessions based on the AMMI stability value; RSY = rank of the accessions based on seed yield across environments. Accessions with the least YSI, i.e. high seed yield and low ASV, are considered superior (Tumuhimbise *et al.*, 2014).

Results

Genotypic correlation

Except for SL and PL, all measured traits had positive significant genotypic relationships with SY (Table 1). The highest genotypic correlation coefficient with SY was recorded by PW ($r_g = 0.89^{**}$), followed by SP ($r_g = 0.76^{**}$), NPPL ($r_g = 0.53^{**}$) and DM ($r_g = 0.45^{**}$). Pod length had a significant relationship ($r_g = -0.44^{**}$) with SY. Significant positive genotypic correlations were also recorded between yield-related traits. Days to flowering was significantly correlated with DM, SP, PL, NLPD and NSPD. Pod filling time, PW, SP, PL and NLPD were significantly correlated with DM. The associations between NPPL on the one hand, and PW and SP on the other were significant. Also, PW was significantly correlated with SP, NLPD, 100-seed weight (HSW), seed width (SW) and seed thickness (ST). Hundred-seed weight, SL, SW and ST were also significantly associated with one another (Table 1).

Path coefficient analysis

Path coefficient analysis revealed that DM (1.493), PW (0.839), SP (0.389) and NSPD (0.155) had positive direct effects on SY, whereas the direct effects of PFT (−1.757), DF (−1.452), NPPL (−0.290) and NLPD (−0.109) on SY were negative (Table 2). Days to flowering had positive indirect effects on SY through DM (0.523) and SP (0.112). Pod filling time had positive indirect influence on SY through DM (0.796) and PW (0.338). Number of pods/plant positively contributes indirectly to SY through PW (0.595) and SP (0.304). Pod length also indirectly influenced SY through DM (0.306). Number of locules/pod indirectly influences SY through DM (0.306), PW (0.160), NSPD (0.151) and SP (0.120). Seed length had an indirect contribution to SY through DM (0.219). Seed width had an indirect effect on SYPL through PW (0.212) and SP (0.167). The residual value of 0.30 was recorded.

Yield stability index

The analysis of the AMMI model for SY revealed highly significant ($P \leq 0.01$) variations among accessions, environments, accession × environment interaction and interaction principal components 1, 2 and 3 (Table 3). Accessions significantly contributed 9.2% to the total sum of squares, while environment and accessions × environment interaction contributed 53.4 and 37.3%, respectively. By partitioning the interaction term through the AMMI model, the first three multiplicative terms (PC1, PC2 and PC3) of AMMI significantly explained 51.0, 24.2 and 12.2% of the interaction sum of squares (Table 3).

Table 1. Genotypic correlation coefficients among 14 traits of 196 accessions of African yam bean evaluated in six environments

Traits	DF	DM	PFT	NPPL	PW	SP	PL	NLPD	NSPD	HSW	SL	SW	ST
DM	0.35**												
PFT	−0.61**	0.53**											
NPPL	−0.57**	0.01	0.53**										
PW	−0.15*	0.32**	0.4**	0.71**									
SP	0.29**	0.4**	0.12	0.78**	0.70**								
PL	0.35**	0.21**	−0.14	−0.33**	−0.23**	−0.83**							
NLPD	0.48**	0.21**	−0.2	0.12	0.19**	0.31**	0.01						
NSPD	0.31**	0.09	−0.14	0.01	0.11	0.27**	−0.08	0.97**					
HSW	0.09	0.12	0.05	−0.18*	0.26**	0.28**	0.11	−0.27**	−0.28**				
SL	0.03	0.15*	0.09	−0.16*	0.07	−0.21**	0.42**	−0.25**	−0.36**	0.73**			
SW	0.01	0.07	0.07	−0.16*	0.25**	0.43**	0.04	0.06	−0.01	0.86**	0.50**		
ST	0.09	0.09	0.05	−0.2**	0.28**	0.5**	−0.02	0.14	0.15*	0.7**	0.19**	0.82**	
SY	0.28**	0.45**	0.15*	0.53**	0.89**	0.76**	−0.44**	0.26**	0.20**	0.29**	−0.06	0.36**	0.41**

*, **, significant at 0.05 and 0.01 probability levels, respectively.
DF, days to flowering; DM, days to maturity; PFT, pod filling time; NPPL, number of pods/plant; PW, pod weight; SP, shelling percentage; PL, pod length; NLPD, number of locules/pod; NSPD, number of seeds/pod; HSW, 100-seed weight; SL, seed length; SW, seed width; ST, seed thickness; SY, seed yield.

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Table 2. Path analysis showing the direct (diagonal bold) and indirect effect of 13 agronomic traits on seed yield of 196 accessions of African yam bean evaluated in six environments

Traits	DF	DM	PFT	NPPL	PW	SP	PL	NLPD	NSPD	HSW	SL	SW	ST	Total correlation with SY
DF	**−1.4520**	0.5229	1.0691	0.1644	−0.1230	0.1115	−0.0050	−0.0522	0.0473	0.0011	−0.0021	−0.0001	0.0015	0.2834
DM	−0.5085	**1.4934**	−0.9362	−0.0042	0.2706	0.1568	−0.0029	−0.0223	0.0137	0.0015	−0.0090	−0.0008	0.0015	0.4536
PFT	0.8834	0.7956	**−1.7573**	−0.1526	0.3383	0.0483	0.0019	0.0216	−0.0211	0.0006	−0.0054	−0.0009	0.0009	0.1533
NPPL	0.8223	0.0216	−0.9237	**−0.2903**	0.5950	0.3040	0.0046	−0.0135	0.0014	−0.0022	0.0098	0.0020	−0.0034	0.5276
PW	0.2128	0.4815	−0.7083	−0.2058	**0.8394**	0.2738	0.0033	−0.0207	0.0175	0.0031	−0.0041	−0.0031	0.0046	0.8940
SP	−0.4160	0.6016	−0.2182	−0.2267	0.5905	**0.3892**	0.0117	−0.0334	0.0424	0.0034	0.0128	−0.0053	0.0084	0.7604
PL	−0.5142	0.3062	0.2429	0.0959	−0.1964	−0.3236	**−0.0141**	−0.0010	−0.0131	0.0013	−0.0260	−0.0005	−0.0003	−0.4429
NLPD	−0.6978	0.3063	0.3490	−0.0360	0.1602	0.1197	−0.0001	**−0.1086**	0.1510	−0.0032	0.0152	−0.0007	0.0023	0.2573
NSPD	−0.4429	0.1324	0.2395	−0.0026	0.0948	0.1065	0.0012	−0.1057	**0.1550**	−0.0034	0.0222	0.0001	0.0025	0.1996
HSW	−0.1366	0.1866	−0.0919	0.0531	0.2195	0.1105	−0.0016	0.0297	−0.0447	**0.0118**	−0.0451	−0.0106	0.0116	0.2923
SL	−0.0499	0.2191	−0.1557	0.0464	0.0557	−0.0809	−0.0059	0.0268	−0.0561	0.0087	**−0.0614**	−0.0062	0.0032	−0.0562
SW	−0.0098	0.0983	−0.1294	0.0468	0.2117	0.1672	−0.0006	−0.0065	−0.0015	0.0102	−0.0306	**−0.0124**	0.0137	0.3571
ST	−0.1313	0.1379	−0.0914	0.0590	0.2328	0.1954	0.0002	−0.0147	0.0232	0.0083	−0.0118	−0.0102	**0.0166**	0.4140

Residual = 0.303, coefficient of determination = 0.9083.
DF, days to flowering; DM, days to maturity; PFT, pod filling time; NPPL, number of pods/plant; PW, pod weight; SP, shelling percentage; PL, pod length; NLPD, number of locules/pod; NSPD, number of seeds/pod; HSW, 100-seed weight; SL, seed length; SW, seed width; ST, seed thickness.

The SY of the accessions ranged from 31.6 g/plant for accession TSs-421 to 6.2 g/plant for accession TSs-309 with a mean of 15.3 g/plant. Half (50.0%) of the AYB accessions in this study had a SY greater than 15.0 g/plant. The ASV of the accessions ranged from 0.018 for accession TSs-143 to 2.139 for accession TSs-195 (Table 4). Based on YSI criterion, accessions TSs-119 (12), TSs-101 (22), 138A (29), TSs-4 (39), TSs-157A (39), TSs-61 (49), TSs-63A (52), 55A (77), TSs-280 (78), TSs-56 (79) and TSs-10A (79) were the top-ranking accessions. Accessions TSs-421 (93) and TSs-195 (102) had the highest mean seed yield per plant and high ASV. Accession TSs-143 though had the lowest ASV, had a mean seed yield below the grand mean. Accessions such as TSs-104, TSs-363, TSs-29, TSs-278, TSs-19, TSs-443 and TSs-11 were low-yielding accessions with high ASV.

Discussion

Genotypic correlation

Genotypic correlation coefficients were used in this study to give an indication of true associations, while excluding environmental influences associated with phenotypic correlation (Kang, 2015). The significant negative association between SY and PL suggests that longer pods may not necessarily translate to higher seed yield in AYB. This finding is consistent with the report of Osuagwu *et al.* (2014), that longer pods may not necessarily translate to high seed yield in AYB. The finding also challenges conventional assumptions and highlights the importance of evidence-based selection criteria in breeding programmes. The positive significant genotypic association between SY and other traits is useful in indirect selection to improve seed yield. Ibirinde and Aremu (2013), Aremu *et al.* (2019) and Alake and Porbeni (2020) reported similar results for different traits in AYB. Simultaneous improvement of these yield-related traits could also be possible due to their significant positive associations. The high genotypic correlation coefficients between SY and PW, SP, NPPL and DM suggest that breeding efforts focused on these traits would be most effective for improving seed yield in AYB. However, the results also suggest potential trade-offs in selection, particularly regarding the association between DM and SY. While longer maturity showed a positive correlation with yield, practical considerations such as growing season length and growers' preferences may necessitate finding an optimal balance between DM and SY potential.

Path coefficient analysis

In the present study, the high coefficient of determination (0.9083) indicates that the analysed traits effectively explain approximately 91% of the total variation in SY, suggesting that our model captured the most significant yield-determining factors. The residual value of 0.30 suggests that 30% of the variation in SY of the AYB accessions is influenced by factors not included in this study, suggesting opportunities for further investigation of additional yield-related traits. The positive direct effects of DM, PW, SP, NSPD, HSW and ST on SY indicated the need to place special emphasis on these traits for the genetic improvement of SY in AYB. Using fewer number of AYB accessions, Nwofia *et al.* (2013) had earlier reported a similar effect of HSW on SY in AYB, while Aremu *et al.* (2019) identified NSPD and DM as important first-order predictor variables of SY. Though DM

Table 3. Analysis of AMMI model for seed yield of 196 accessions of African yam bean evaluated in six environments and the proportion of the total variance attributable to the sources of variation

Source of variation	DF	SS	MS	% G × E interaction	% SS
Environment	5	297613.0	59,522.59***		53.43
Accession	195	51460.5	263.9***		9.24
Interaction	975	207984.9	213.32***		37.34
IPCA1	199	100915.6	507.11***	51.04	
IPCA2	197	47746.0	242.37***	24.15	
IPCA3	195	24852.99	127.45**	12.57	
Residuals	2271	333636.0	146.91		

, * significant at *P*-value <0.01 and <0.001, respectively.
DF, the degree of freedom; SS, the sum of square; MS, mean square.

Table 4. Mean seed yield, AMMI stability value, yield stability indices and their ranks for the 196 accessions of African yam bean evaluated in six environments

Accession	SY	IPCA1	IPCA2	ASV	RASV	RSY	YSI	YSIR
TSs-119	25.67	0.01405	0.04952	0.05774	7	5	12	1
TSs-101	24.06	0.03266	−0.04270	0.08119	14	8	22	2
138A	19.23	0.01680	0.01530	0.03866	3	26	29	3
TSs-4	19.78	−0.03480	−0.04810	0.08787	16	23	39	4
TSs-157A	18.59	−0.00290	0.05649	0.05683	6	33	39	5
TSs-61	18.52	−0.03100	−0.05080	0.08296	15	34	49	6
TSs-63A	22.52	0.02934	−0.17370	0.18445	41	11	52	7
55A	17.08	0.03101	−0.07220	0.09751	18	59	77	8
TSs-280	16.15	0.01347	−0.01080	0.03046	2	76	78	9
TSs-10A	18.20	−0.08350	0.07257	0.19082	43	36	79	10
TSs-56	17.00	−0.04690	−0.01060	0.09963	19	60	79	11
TSs-87	17.31	0.01901	−0.14540	0.15088	32	51	83	12
TSs-427	17.43	0.08635	−0.02670	0.18444	40	45	85	13
151B	15.94	−0.00950	−0.05720	0.06068	8	80	88	14
TSs-186	17.35	0.00584	0.19138	0.19177	44	49	93	15
TSs-26	15.63	0.03070	−0.02940	0.07126	12	83	95	16
TSs-55	17.79	−0.05860	0.17298	0.21273	57	40	97	17
119A	16.41	−0.04380	−0.09780	0.13468	28	73	101	18
7A	15.93	−0.01010	−0.09840	0.10071	21	81	102	19
TSs-68	15.53	−0.02630	−0.07030	0.08960	17	85	102	20
TSs-12	21.29	−0.08120	−0.24620	0.30015	87	16	103	21
TSs-361	15.09	0.02313	−0.03960	0.06289	9	94	103	22
TSs-282	17.24	−0.08810	−0.08300	0.20380	51	54	105	23
TSs-301	16.34	−0.04820	−0.10890	0.14915	31	75	106	24
TSs-157	20.46	−0.15150	−0.00570	0.32017	92	20	112	25
TSs-84	14.30	−0.02220	−0.01890	0.05060	4	108	112	26
TSs-66	17.25	−0.10410	0.00177	0.22008	60	53	113	27
56A	16.71	0.02107	−0.19200	0.19708	49	65	114	28
TSs-111	15.42	−0.05700	0.02562	0.12320	26	89	115	29
60B	18.85	−0.14570	−0.00140	0.30794	88	30	118	30

(*Continued*)

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Table 4. (*Continued.*)

Accession	SY	IPCA1	IPCA2	ASV	RASV	RSY	YSI	YSIR
TSs-116	17.17	0.07171	−0.17990	0.23524	65	56	121	31
TSs-69	13.85	−0.00970	0.04951	0.05355	5	117	122	32
TSs-294	14.79	0.03901	0.05980	0.10186	22	101	123	33
TSs-366	17.50	0.13037	−0.05870	0.28173	80	44	124	34
TSs-424	22.38	−0.18250	0.13093	0.40729	113	12	125	35
TSs-138	14.82	0.05569	−0.01460	0.11861	25	100	125	36
TSs-307	17.11	−0.07240	0.19744	0.24985	69	58	127	37
TSs-268	15.84	0.06720	−0.12970	0.19234	46	82	128	38
TSs-119A	18.89	−0.16530	0.01862	0.34985	101	28	129	39
TSs-48	21.42	0.14824	−0.32260	0.44971	119	15	134	40
TSs-33	16.80	−0.11580	−0.07050	0.25471	72	62	134	41
TSs-293	16.52	0.04609	−0.21610	0.23703	66	70	136	42
TSs-313	13.51	−0.00070	0.06949	0.06951	11	125	136	43
TSs-22B	13.50	−0.01410	−0.05780	0.06509	10	126	136	44
TSs-60	14.89	0.05731	−0.13470	0.18113	39	99	138	45
30B	16.58	0.11884	−0.03900	0.25418	71	69	140	46
TSs-45	14.17	−0.04350	0.10088	0.13650	29	111	140	47
TSs-274	15.14	0.08766	0.09292	0.20728	53	93	146	48
TSs-296	16.77	−0.11730	0.15717	0.29356	83	64	147	49
TSs-450	16.62	0.11068	0.15413	0.28013	79	68	147	50
TSs-84A	26.18	−0.01640	−0.56280	0.56387	145	3	148	51
TSs-317	14.62	0.03142	−0.18040	0.19223	45	105	150	52
TSs-86	13.89	−0.00570	0.15936	0.15981	34	116	150	53
TSs-255	18.81	0.02945	−0.44770	0.45197	120	31	151	54
TSs-166	17.72	−0.16040	0.19793	0.39259	110	41	151	55
TSs-297	16.41	0.12083	0.11191	0.27884	78	74	152	56
TSs-299	12.57	0.03587	0.01373	0.07705	13	142	155	57
TSs-440	18.64	−0.20430	−0.17970	0.46768	124	32	156	58
TSs-5	15.03	0.09216	−0.11430	0.22585	61	97	158	59
TSs-369	25.08	−0.04050	−0.59050	0.59671	153	6	159	60
TSs-46	17.22	−0.14330	−0.24190	0.38764	109	55	164	61
TSs-63	15.08	0.10249	−0.12660	0.25093	70	95	165	62
TSs-1	14.76	−0.06780	0.18544	0.23430	64	103	167	63
TSs-357	13.64	−0.02620	−0.18670	0.19475	47	120	167	64
TSs-38	15.24	−0.11160	0.14753	0.27821	77	92	169	65
TSs-143	11.10	−0.00380	0.01640	0.01823	1	168	169	66
TSs-275	13.85	−0.07850	0.12541	0.20791	55	118	173	67
TSs-433	12.75	−0.04980	0.12591	0.16411	37	137	174	68
TSs-365	23.61	−0.30280	−0.26490	0.69262	166	9	175	69
TSs-151B	22.65	−0.31170	0.10672	0.66738	165	10	175	70
TSs-153	20.32	−0.28010	0.09632	0.59985	154	21	175	71
TSs-168	16.69	−0.18070	−0.06600	0.38760	108	67	175	72
TSs-437	15.38	−0.12200	−0.14970	0.29823	86	90	176	73

(*Continued*)

Table 4. (*Continued.*)

Accession	SY	IPCA1	IPCA2	ASV	RASV	RSY	YSI	YSIR
TSs-120	13.29	−0.08650	0.06798	0.19509	48	129	177	74
TSs-136	16.49	0.15016	−0.21960	0.38591	107	71	178	75
TSs-162	21.02	0.30720	0.06068	0.65212	162	17	179	76
TSs-1A	14.50	0.04944	0.24477	0.26615	73	106	179	77
59B	20.51	−0.30460	−0.06320	0.64692	161	19	180	78
TSs-23C	16.70	−0.19530	0.03207	0.41410	114	66	180	79
44C	13.62	0.09852	−0.05810	0.21619	59	122	181	80
TSs-23	19.42	0.15838	−0.54700	0.64134	157	25	182	81
TSs-438	12.39	−0.08140	−0.03370	0.17537	38	147	185	82
61A	17.41	−0.25380	0.08406	0.54306	140	47	187	83
TSs-60B	17.34	0.23531	0.15825	0.52192	137	50	187	84
TSs-22A	13.17	−0.10170	−0.01280	0.21543	58	130	188	85
TSs-113	18.92	0.18478	−0.52970	0.65810	164	27	191	86
TSs-302	14.49	0.13893	0.03334	0.29552	84	107	191	87
TSs-358	12.33	0.07944	0.08154	0.18665	42	150	192	88
TSs-144	18.34	−0.01270	−0.64150	0.64202	158	35	193	89
TSs-42	17.29	−0.22580	−0.26570	0.54627	141	52	193	90
TSs-266	14.15	0.11877	−0.13020	0.28278	81	112	193	91
TSs-14	21.00	−0.36040	0.00909	0.76181	176	18	194	92
TSs-421	31.63	−0.85190	−0.72250	1.94011	194	1	195	93
TSs-67	10.84	0.03506	0.08672	0.11407	24	171	195	94
TSs-192	26.07	−0.57090	0.05517	1.20800	192	4	196	95
TSs-13	15.07	0.15465	0.11116	0.34525	100	96	196	96
TSs-155	21.54	−0.36430	−0.36830	0.85360	183	14	197	97
104B	15.24	−0.14490	0.22733	0.38134	106	91	197	98
TSs-338	12.55	0.09808	0.00581	0.20739	54	143	197	99
TSs-367	11.71	−0.05300	0.11403	0.15981	35	162	197	100
TSs-333	10.89	0.04371	−0.08620	0.12635	27	170	197	101
TSs-195	27.54	−1.00000	0.33151	2.13943	196	2	198	102
TSs-249	14.19	−0.13410	0.13163	0.31253	90	109	199	103
TSs-287	14.19	0.07091	0.27275	0.31122	89	110	199	104
TSs-311	13.03	−0.09180	0.15100	0.24594	68	132	200	105
TSs-87B	17.12	−0.26290	−0.04300	0.55743	144	57	201	106
TSs-368	10.10	−0.04730	0.00896	0.10028	20	181	201	107
TSs-133	24.09	−0.94900	0.21084	2.01695	195	7	202	108
TSs-96	17.70	0.30356	0.06865	0.64527	160	42	202	109
TSs-93	17.37	−0.28850	−0.03120	0.61059	155	48	203	110
TSs-285	16.93	0.22939	0.26972	0.55482	143	61	204	111
TSs-337	22.12	−0.74220	0.01346	1.56882	193	13	206	112
TSs-148	17.83	−0.33700	−0.00210	0.71223	168	38	206	113
TSs-277	10.42	0.05045	0.11883	0.15965	33	175	208	114
TSs-445	20.02	−0.44300	0.05237	0.93786	187	22	209	115
TSs-6B	19.63	−0.41270	−0.07880	0.87573	185	24	209	116

(*Continued*)

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Table 4. (*Continued.*)

Accession	SY	IPCA1	IPCA2	ASV	RASV	RSY	YSI	YSIR
159A	12.90	−0.11060	0.13149	0.26829	74	135	209	117
63A	17.52	−0.32630	0.11702	0.69962	167	43	210	118
TSs-314	11.89	−0.09630	0.02528	0.20518	52	158	210	119
TSs-44C	18.85	−0.37680	0.17093	0.81458	182	29	211	120
TSs-82	9.17	0.04866	0.02120	0.10502	23	189	212	121
TSs-442	13.99	0.12110	0.22107	0.33820	98	115	213	122
23C	11.93	0.06502	0.15848	0.20977	56	157	213	123
TSs-137	16.79	−0.28070	0.02594	0.59386	151	63	214	124
TSs-6A	15.44	−0.23190	0.07189	0.49536	128	87	215	125
TSs-8	17.79	−0.36300	−0.01610	0.76749	177	39	216	126
TSs-7A	16.09	0.25153	0.09115	0.53939	139	78	217	127
62B	14.76	0.20135	−0.06750	0.43089	117	102	219	128
TSs-5A	14.94	−0.21630	−0.07460	0.46322	122	98	220	129
TSs-66A	17.42	0.22386	−0.60760	0.77011	178	46	224	130
TSs-44	12.68	0.11277	0.17747	0.29716	85	139	224	131
TSs-217	8.33	0.05978	0.07607	0.14748	30	194	224	132
TSs-212	13.62	−0.13840	0.22378	0.36834	104	121	225	133
TSs-224	17.93	−0.50360	0.11884	1.07099	191	37	228	134
TSs-441	16.00	−0.27640	0.04538	0.58590	149	79	228	135
TSs-378	15.51	−0.25350	0.11288	0.54765	142	86	228	136
TSs-150	16.14	−0.28160	−0.01980	0.59546	152	77	229	137
TSs-98	12.85	0.07018	0.28425	0.32063	93	136	229	138
TSs-309	6.20	−0.01840	0.15592	0.16069	36	196	232	139
TSs-59	9.91	0.03365	0.18463	0.19785	50	184	234	140
TSs-6	10.63	0.09498	−0.10610	0.22706	62	173	235	141
TSs-121	13.66	0.14950	0.29778	0.43419	118	119	237	142
TSs-30	12.99	0.13363	−0.24010	0.37067	105	133	238	143
TSs-371	11.48	0.12783	−0.03820	0.27287	76	163	239	144
TSs-92	14.12	0.08488	−0.45750	0.49142	127	113	240	145
TSs-24	16.47	0.34522	−0.15470	0.74587	172	72	244	146
89A	12.34	0.12123	−0.20970	0.33112	97	149	246	147
TSs-56A	15.44	0.29494	−0.15800	0.64309	159	88	247	148
TSs-377	10.74	0.09434	0.18317	0.27075	75	172	247	149
TSs-156A	13.51	−0.22130	0.10125	0.47859	125	124	249	150
TSs-3	12.42	0.14501	0.20013	0.36605	103	146	249	151
TSs-320	12.17	0.01211	0.32576	0.32677	96	153	249	152
TSs-326	9.42	0.10688	0.05854	0.23336	63	188	251	153
TSs-10	12.54	0.18408	−0.11560	0.40589	111	145	256	154
TSs-31	8.93	0.05287	0.21812	0.24507	67	190	257	155
TSs-276	15.57	−0.35560	0.07283	0.75514	175	84	259	156
TSs-331	11.34	0.15450	0.00224	0.32655	95	164	259	157
TSs-28	12.97	0.19656	0.24059	0.48009	126	134	260	158
TSs-422	12.72	0.21612	0.09188	0.46593	123	138	261	159

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Table 4. (*Continued.*)

Accession	SY	IPCA1	IPCA2	ASV	RASV	RSY	YSI	YSIR
TSs-298	12.37	0.14796	0.27868	0.41888	115	148	263	160
TSs-22	12.30	0.19177	−0.03921	0.40722	112	151	263	161
TSs-435	13.44	0.19551	−0.33047	0.52912	138	127	265	162
TSs-216	11.25	0.06758	0.33690	0.36592	102	166	268	163
TSs-273	10.55	0.14586	0.09005	0.32117	94	174	268	164
TSs-269	12.58	0.22668	0.17637	0.51054	132	141	273	165
TSs-47	8.54	0.11600	0.14580	0.28526	82	193	275	166
30A	9.87	−0.07680	0.26836	0.31364	91	185	276	167
TSs-2015-06	14.73	0.35149	−0.07873	0.74708	173	104	277	168
TSs-15	14.04	0.30683	0.10850	0.65753	163	114	277	169
TSs-16	12.54	0.23936	0.07299	0.51114	133	144	277	170
TSs-34	12.00	0.24072	0.02029	0.50919	131	155	286	171
TSs-90	9.52	0.15994	0.06016	0.34335	99	187	286	172
TSs-7	12.03	0.23645	−0.11668	0.51319	135	154	289	173
TSs-51	11.99	0.24230	−0.04561	0.51415	136	156	292	174
TSs-289	10.21	0.19486	0.09138	0.42187	116	179	295	175
TSs-159A	10.40	0.21239	0.07203	0.45464	121	176	297	176
TSs-151A	13.16	0.31520	−0.25238	0.71241	169	131	300	177
TSs-161	13.39	0.34614	0.31585	0.79687	181	128	309	178
TSs-201	11.72	0.26259	0.19043	0.58676	150	160	310	179
TSs-62	10.14	0.23928	−0.02988	0.50663	130	180	310	180
TSs-39A	11.33	0.25549	0.16891	0.56579	146	165	311	181
TSs-304	10.01	0.18794	0.29832	0.49679	129	182	311	182
TSs-32	13.60	0.48587	−0.14758	1.03749	190	123	313	183
TSs-434	10.27	0.27342	0.06603	0.58166	147	178	325	184
TSs-312	8.69	0.24207	0.00560	0.51167	134	192	326	185
TSs-115	12.64	0.45734	−0.21029	0.98923	189	140	329	186
TSs-49	11.72	0.34209	−0.11466	0.73208	171	161	332	187
TSs-62B	11.75	0.35292	0.04947	0.74758	174	159	333	188
TSs-3A	12.21	0.40533	0.15769	0.87109	184	152	336	189
TSs-11	9.94	0.27514	0.24162	0.62973	156	183	339	190
TSs-443	7.46	0.26875	0.13130	0.58301	148	195	343	191
TSs-19	11.16	−0.22291	−0.60921	0.77014	179	167	346	192
TSs-278	11.10	0.36462	−0.05294	0.77247	180	169	349	193
TSs-29	9.80	0.32886	0.18443	0.71913	170	186	356	194
TSs-363	10.37	−0.43499	0.36008	0.98738	188	177	365	195
TSs-104	8.83	0.41745	0.08941	0.88685	186	191	377	196

SY, seed yield (g/plant); IPCA, interaction principal component (PC); ASV, AMMI stability value; RSY, rank of seed yield; RASV, rank based on AMMI stability value; YSI, yield stability index; YSIR, yield stability index rank.

exhibited the highest positive direct effect on SY, DF and PFT had a strong negative direct effect, suggesting a complex relationship between these phenological traits and yield. This indicates that early flowering combined with longer PFT might be optimal for yield improvement through indirect selection.

Apart from DF and PFT, other traits such as NPPL, NLPD and SW had a negative direct effect on SY, despite having significant positive genotypic correlations with SY. This was due to their positive indirect effects on SY through other traits. For instance, DF and PFT had a high positive indirect effect on SY via DM,

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suggesting that selection for these traits would be effective and hence influence SY and DM indirectly. This complex interaction emphasizes the need for careful consideration of trait relationships in breeding programmes. The negative direct effect of NPPL was unexpected given its positive correlation with yield, highlighting the importance of considering both direct and indirect effects in selection decisions.

Yield stability index

The YSI was used to identify stable accessions with good SY performance. The high contribution of environment (53.4%) to the total sum of squares indicated that environmental diversity caused most of the observed variation in SY. The higher magnitude of accession × environment interaction sums of squares compared to that of accession indicated the differential response of accessions in the environments and crossover genotype × environment interaction effects for SY. A similar result was reported by Aremu *et al.* (2020) in AYB. The relatively smaller genotypic contribution to total variation, while still significant, suggests that genetic differences among accessions were masked by environmental effects and G × E interactions. This further buttress the need to employ selection strategies that account for both yield potential and stability. The high proportion explained by IPCA1 (51.0%) suggests that a considerable portion of the genotype response patterns can be captured by this first component, providing a reliable basis for selecting stable genotypes.

Accessions TSs-119, TSs-101, 138A, TSs-4, TSs-157A and TSs-61 were ranked most desirable, integrating stability with high mean seed yield. These accessions represent valuable germplasm for breeding programmes targeting broad environmental adaptation. A similar result had been reported by Aremu *et al.* (2020) for TSs-61. Accessions TSs-143, TSs-280, 138A, TSs-84, TSs-69, TSs-157A, TSs-119, 151B, TSs-361 and TSs-22B with the lowest ASV were the most stable of the 196 accessions studied across the six environments. In a study involving 23 accessions of AYB, Aremu *et al.* (2020) also reported TSs-69 as one of the most stable accessions in SY. In another study involving 30 AYB accessions, Adewale (2016) identified accession TSs-84 as the most stable for 100-seed weight. Although accession TSs-143 was the most stable, it was not the most desirable due to its low SY, while accessions TSs-421 and TSs-195, which had the highest SY, were not the most desirable. These findings buttress the fact that stable genotypes do not necessarily give the best performance and vice versa (Bose *et al.*, 2014). While the stability trait of accessions like TSs-143 with low SY and high ASV could be valuable, their use in breeding programmes would need to be carefully considered to avoid compromising yield potential. Furthermore, the lower but consistent yield character of these accessions could reflect conservative resource management strategies which are particularly valuable under limited resource conditions. Also, while high-yielding accessions with low ASV may not be suitable for broad deployment, they could be valuable in breeding programmes targeting specific environments. Accessions such as TSs-104, TSs-363, TSs-29, TSs-278, TSs-19, TSs-443 and TSs-11 were low yielding and less stable, hence, they are least desirable. However, they may possess other valuable traits not captured in this study.

Conclusion

This study revealed days to maturity, pod weight, shelling percentage, number of seeds per pod, 100-seed weight and seed thickness as important traits that should be included in a selection criterion for improved seed yield in AYB. Further studies on marker–trait association for these traits should be encouraged to accelerate the genetic improvement of AYB for seed yield. Accessions TSs-119, TSs-101, 138A, TSs-4, TSs-157A and TSs-61, which combined superior seed yield with stability, should be considered in future breeding programmes for seed yield improvement. The identification of stable, high-yielding accessions and key yield-related traits provides a framework for accelerating AYB improvement across diverse agro-ecologies, while offering a valuable model for breeding programmes of other underutilized legumes in similar environmental conditions.

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