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THE FRUIT METRIC TRAIT CHARACTERIZATION OF SCARLET EGGPLANT USING THE HIGH-THROUGHPUT TOMATO ANALYZER SOFTWARE

Olawale Taiwo Adeniji[1*], Modinat Adekoya[2], Peter Jonah[3], Innocent Iseghohi[1] and Charity Aremu[4]

[1]Department of Crop Science and Horticulture,
Federal University Oye Ekiti, Nigeria
[2]Department of Plant Science and Biotechnology,
Federal University Oye Ekiti, Nigeria
[3]Department of Crop Science, Adamawa State University, Mubi, Nigeria
[4]Department of Crop Production, Landmark University,
Omuaran, Kwara State, Nigeria

Abstract: Scarlet eggplant (*Solanum aethiopicum* [L.]) is an indigenous, underutilized fruit vegetable in Africa. Preference for fruit shape and size is high among growers and consumers. Fruit metric traits are important for yield improvement. Fruit metric descriptors are important contributors to variation, phenotypic and genotypic variation, and heritability. However, the measurement of these traits is cumbersome and subjective. Forty-three accessions were evaluated in 2016 and 2017. At maturity, 5 fruits were randomly harvested from each accession, digitalized and processed using the Tomato Analyzer software. Sixteen fruit metric traits were automatically generated and submitted for analysis of variance and multivariate analysis. The accessions differed over fruit size and shape due to genetic make-up. Fruit metric trait variation among *S. aethiopicum* groups was less influenced by the environment. The cv. Gilo group has oblong fruits, the cv. Shum group fruits are circular and ovoid; the cv. Kumba group fruits are less circular, lobed and flattened. AE/113 (C3), FUO 1 (C1) and FUO 5 (C2) Gilo groups are promising for fruit size. There were phenotypic plasticity and overlapping for fruit metric traits between the Gilo and Shum groups due to a common genome. The Tomato Analyzer software was able to discriminate accessions based on fruit phenomic traits, and the information could be used to establish commonalities between groups.

Key words: *Solanum aethiopicum*, fruit area, fruit size, genetic diversity, heritability.

[*]Corresponding author: e-mail: olawale.adeniji@fuoye.edu.ng

Introduction

Scarlet eggplant (*Solanum aethiopicum* [L.]) has 4 cultivar groups (Aculeatum, Gilo, Kumba and Shum), with overlapping of morphological and agronomic traits (Levin, 2005; Adeniji et al., 2013), and it is able to tolerate varying environments (Shippers, 2002; Adeniji et al., 2013). Consumer choice for fresh fruit depends on external appearance, where cream or white fruit color at physiological ripeness, fruit shape, fruit length, fruit width and degree of fruit lobbing are factors determining purchase (Adeniji and Aloyce, 2012).

Fruit shape and size development depend on processes taking place during fruit formation. The assessment of variation in scarlet eggplant using morphological descriptors and agronomic traits contributes to understanding differentiation in phenotypes (Polignano et al., 2010; Adeniji et al., 2012, 2013). Based on morphological descriptors, fruits of scarlet eggplant are categorized into 10 shapes (Anonymous, 1996). Within the characterization of morphological traits, fruit shape is a non-ordered trait, usually coded as oblate, flattened, heart-shaped, pyriform and ellipsoidal round, oval, and squat in tomato (*Solanum lycopersicum* [L.]) (Anonymous, 1996) and eggplant (Anonymous, 2003). This does not provide realistic information on fruit shape. The phenotypic measurement of physical fruit characteristics is laborious, time-consuming, and unreliable. Tomato and scarlet eggplant groups belong to the family Solanaceae. Some fruits of each plant are similar in size and shape. Fruit shape attributes can be measured with precision using scanned images of fruit sections (Brewer et al., 2007; Gonzalo and van der Knaap, 2008). The Tomato Analyzer software has been used for fruit morphometric and metric trait analysis in tomato and eggplant (Rodriguez et al., 2010; Hurtado et al., 2013). This technique allows for the precise measurement of fruit size and shape.

The market demand for the scarlet eggplant fruit is associated with its nutritional health benefits. Challenges in realizing the best yield of this crop include the absence of commercial varieties with consumer-preferred fruit metric traits. The availability of this information could provide a phenotypic classification of fruit characteristics essential for discrimination among accessions. In addition, information on fruit metric traits, through diversity analysis, will add to the existing information on morphological and agronomic trait characterization of scarlet eggplant groups, hasten the identification of pollen parents and promising accessions for field evaluation. This study was undertaken to identify fruit metric descriptors that are the most important contributors to fruit metric variation among scarlet eggplant groups, evaluate the magnitude of variation for fruit metric traits, estimate heritability and identify promising accessions for genetic enhancement.

Material and Methods

Forty-one accessions and a variety DB_3 (check) of scarlet eggplant (Table 1) were obtained from the southwest, north-central and northeast regions in Nigeria between August 2015 and July 2016. Seedling production and field planting took place between May and September 2016 and 2017 at the Teaching and Research Farm of the Department of Crop Science and Horticulture, Federal University Oye Ekiti, Nigeria (longitude 7°07'N, latitude 5°49'E, altitude 554.4 m asl). The physico-chemical properties of the soil (0–25 cm depth) from the research field indicated a pH of 5.7 (in H_2O, 1:1), OM (%) 0.82, N (%) 0.08, available phosphorus (Bray Method) 219.33, exchangeable Mg (C mol·kg^{-1}) 0.19, exchangeable K (C mol·kg^{-1}) 0.48, exchangeable Na (C mol·kg^{-1}) 0.07, exchangeable Ca (C mol·kg^{-1}) 2.93, ECEC, 3.68, Zn (mg·kg^{-1}) 1.12, Cu (mg·kg^{-1}) 1.01, Mn (mg·kg^{-1}) 107.7, Fe (mg·kg^{-1}) 180.07, sand 68%, silt 20%, clay 11%, with a sandy loam textural class. The location is characterized by an annual temperature of 24.2°C, precipitation averages of 1,313 mm annually, with September having the highest rainfall, avg. 241 mm.

Table 1. The accessions of *Solanum aethiopicum* and the place of collection.

Sn	Accession code	Place of collection	Sn	Accession code	Place of collection
Acc 1	AE/192	NaGRAB[a], Nigeria	Acc 23	AE/138	NaGRAB, Nigeria
Acc 2	AE/132	NaGRAB, Nigeria	Acc 24	AE/138-2	NaGRAB, Nigeria
Acc 3	AE/1437	NaGRAB, Nigeria	Acc 25	AE/0737	NaGRAB, Nigeria
Acc 4	AE/138	NaGRAB, Nigeria	Acc 26	AE/38	NaGRAB, Nigeria
Acc 5	AE/001	NaGRAB, Nigeria	Acc 27	AE/38-2	NaGRAB, Nigeria
Acc 6	AE/01473	NaGRAB, Nigeria	Acc 28	FUO 8	FUOYE, Nigeria
Acc 7	AE/1370	NaGRAB, Nigeria	Acc 29	FUO 9	FUOYE, Nigeria
Acc 8	AE/128	NaGRAB, Nigeria	Acc 30	EX SIVON	AVRDC[c], Taiwan
Acc 9	AE/113	NaGRAB, Nigeria	Acc 31	FUO 10	FUOYE, Nigeria
Acc 10	FUO 1	FUOYE[b], Nigeria	Acc 32	DB3	AVRDC, Taiwan
Acc 11	FUO 2	FUOYE, Nigeria	Acc 33	MM 1133	AVRDC, Taiwan
Acc 12	FUO 3	FUOYE, Nigeria	Acc 34	SOS	INRA[d], France
Acc 13	FUO 4	FUOYE, Nigeria	Acc 35	FUO 11	FUOYE, Nigeria
Acc 14	AE/130	NaGRAB, Nigeria	Acc 36	FUO 12	FUOYE, Nigeria
Acc 15	AE/1472	NaGRAB, Nigeria	Acc 37	FUO 13	FUOYE, Nigeria
Acc 16	AE/1475	NaGRAB, Nigeria	Acc 38	FUO 14	FUOYE, Nigeria
Acc 17	AE/30	NaGRAB, Nigeria	Acc 39	S.INT	INRA, France
Acc 18	FUO 5	FUOYE, Nigeria	Acc 40	FUO 15	FUOYE, Nigeria
Acc 19	FUO 6	FUOYE, Nigeria	Acc 41	FUO 16	FUOYE, Nigeria
Acc 20	FUO 7	FUOYE, Nigeria	Acc 42	FUO 17	FUOYE, Nigeria
Acc 21	AE/100	NaGRAB, Nigeria			
Acc 22	AE/1473-2	NaGRAB, Nigeria			

[a]NaCGRAB = National Center for Genetic Resources and Biotechnology; [b]FUOYE = Federal University Oye Ekiti, Nigeria; [c]INRA = French Institute for Agricultural Research; [d]AVRDC = Asian Vegetable Research and Development Center.

One seed of each accession was planted in each cell of multipot seedling trays filled with sterilized soil. Water was applied to seedlings with a watering can in the morning and evening for 4 weeks. Prior to the nursery establishment, the field was plowed. Fourteen days later, the soil was harrowed, and ridges made 1 m apart. Seedlings, with adhering soil, were transplanted to the field by hand. The experiment was arranged in a randomized complete block design with 4 replications. Each accession was allotted to a 2-row plot 4 m long and 1 m between rows, with 0.45 m between plants.

Prior to planting, the soil was fertilized with 20N-10P-10K at the rate of 90 kg·ha^{-1} N, 45 kg·ha^{-1} P_2O_5, and 45 kg·ha^{-1} K_2O. Urea fertilizer (46% N) was applied at a total of 120 kg·ha^{-1} in 3 splits at 1 week after transplanting, at flowering and 3 weeks thereafter. Ridomyl® (Matalxyl) WP (fungicide) was applied against damping-off in the field at the rate of 20 g/15 L of water 12 days after transplanting. Selecron® EC (insecticide) was applied 2 weeks after transplanting at 20 mL/20 L of water to control cutworms and other insects. The experiment was furrow-irrigated every 2 days for the first 2 weeks after transplanting, then once a week thereafter. Weeding was carried out manually with hoes.

At maturity, 5 fruits were randomly picked from each accession in a replicate during 2016 and 2017; 20 fruit for each accession. A longitudinal cut was made on each fruit, and fruit halves were digitalized with an HP Scanjet G4010 photo scanner (Hewlett-Packard, Palo Alto, CA) at a resolution of 300 dpi. Before morphometric measurement, a default setting was established for fruit blockiness and proximal and distal fruit end shape. Scanned images were exported to Tomato Analyzer, ver. 3, software (Rodriguez et al., 2010) for measuring morphometric traits. Data were measured for 15 fruit metric traits (Table 2) automatically received from Tomato Analyzer. The fruit morphometric names and measurements were defined by the manufacturer. Morphometric data for fruit descriptors were analyzed for the means, coefficients of variation and ranges. A combined analysis of variance was applied to detect differences among accessions for each fruit morphometric trait. Accession was treated as a fixed trait; the year was a random trait in PROC GLM of SAS (ver. 9.4, SAS Institute, Inc., Cary, NC). Means were separated using the Tukey's HSD test. Variances due to the phenotype (σ^2p) and the genotype (σ^2g) and coefficients of variation associated with the phenotype (PCV) and genotype (GCV) were estimated according to Syukur and Rosidah (2014).

To identify fruit metric attributes with high contribution to variability, the principal component analysis was performed on entry means using the PROC PCA procedure of SAS. A dendrogram was constructed using the unweighted pair group method of analysis with a squared Euclidean distance option (Sokal and Michener, 1958; Ward, 1963) in SPSS (ver. 16.0, IBM Corporation, UK).

Table 2. The phenomic characterization of scarlet eggplant fruits.

Fruit metric trait	Measurement and description
Fruit perimeter	cm
Fruit area	cm^3
Fruit height mid-width	Fruit mid-width height (cm) was calculated as ½ of the fruit's width.
Fruit maximum width	Fruit maximum horizontal distance (cm).
Fruit width mid-height	Fruit width mid-height (cm) was calculated as ½ of the fruit's height.
Fruit maximum height	Maximum height of the fruit (cm) (vertical distance of the fruit).
Fruit shape index internal	Fruit shape index internal computed as the ratio of internal ellipse fruit height to width, a value >1 is elongated, equal to 1 is round, and <1 is short.
Fruit shape index external II	Calculated as the ratio of the fruit height mid-width to its width mid-height.
Proximal eccentricity	Proximal eccentricity determined as the ratio of fruit height of the ellipse to the distance between the ellipse value close to unity is round fruit, less than unity is pear-shaped.
Distal eccentricity	Distal eccentricity measured as the ratio between the vertical axis of the ellipse and distance from the top of the ellipse to the bottom of the fruit, round bottom fruit have distal eccentricity close to 1, slightly pointed fruit have value <1.
Fruit eccentricity	The ratio between internal ellipses of the maximum height.
Fruit curve height	The height measured along a curved line through the fruit (passing through the midpoints of opposing pairs of points on either side of the distal and proximal points).
Fruit shape eccentricity I	Describe how top or bottom heavy a fruit is calculated according to the formula described by Rodríguez et al. (2010).
Fruit shape eccentricity II	Fruit shape eccentricity II is calculated according to the formula described by Rodríguez et al. (2010).
Lobeness	Computed as the standard deviation of distance from the center of the fruit perimeter multiplied by 100.

Results and Discussion

Significant mean squares were recorded among accessions for traits associated with fruit perimeter, area, width mid-height, maximum width, height mid-width, and maximum height. The year and the accession by year interaction were not significant (Table 3). A similar trend was found for traits associated with fruit shape (Table 4). The range of variation was high in fruit perimeter, fruit lobeness, fruit curvature, fruit shape index, curved fruit width, maximum fruit height, maximum fruit width, and fruit area. The accessions of the scarlet eggplant Gilo group (accessions 9, 18 and 10) were best for fruit perimeter, width, and area (Table 5). Accessions 9 (C3), 10 (C1) and 18 (C2) could be pollen parents for improving fruit size through intraspecies hybridization within Gilo, between Gilo and Shum, and Gilo and Kumba groups. Accessions 14 (C3), 19 (C2) 17, had high fruit mid-width height and maximum fruit width values (Table 6), so they are promising for wide fruits. Fruit distal eccentricity was the lowest for Accession 24

(C3a), but the highest for Accession 27 (C3a) (Table 6). Entries with mean values close to 0 corresponded to a pointed fruit tip end, and the fruit with a mean closer to 1 had a round distal fruit end. The scarlet eggplant fruit with a pointed tip end will enhance the packaging and arrangement of fruits in trays. Fruit proximal eccentricity value was low in Accession 18 (C2b) and high in Accession 27 (C3a) (Gilo). Fruit shape index refers to the internal ellipse drawn around the seed area. A fruit shape index of a value greater than 1 indicates an elongated fruit, equal to 1 indicates a round fruit, and less than 1 indicates a squat fruit.

Table 3. Mean squares for fruit metric traits among *Solanum aethiopicum* groups for which significant differences ($P < 0.05$) were found.

Source	Fruit						
	Perimeter	Width mid-height	Max. width	Height mid-width	Max. height	Area	Lobeness
Accession (A)	*	**	*	**	*	*	**
Year (Y)	ns	ns	ns	ns	ns	ns	ns
A × Y	ns	ns	ns	ns	ns	ns	ns

ns, *, ** not significant or significant at P<0.05 or P<0.01, ANOVA.

Table 4. Mean squares for fruit shape among *Solanum aethiopicum* groups for which significant differences ($P < 0.05$) were found.

Source	Fruit							
	Curve height	Shape index internal	Eccentricity	Shape eccentricity I	Shape eccentricity II	Proximal eccentricity	Distal eccentricity	Shape index external II
Accession (A)	*	*	*	*	**	**	*	**
Year (Y)	ns	ns	ns	ns	ns	ns	ns	ns
A × Y	ns	ns	ns	ns	ns	ns	ns	ns

ns, *, ** not significant or significant at P<0.05 or P<0.01, ANOVA.

Accessions with the round fruit are more frequent than accessions with pear-shaped fruits. The fruit shape eccentricities I and II were high in Accessions 10, 18 and 41 (Gilo) (Table 6). Fruit lobes measure the degree of an uneven shape of a fruit. Accessions 1, (C2b) 3, (Outlier) 4 (Outlier), 10 (C1b), 17 (Outlier), 18 (C2b), 32 (C1a), 35 (C4), 37 (C4), 38 (C4), 39 (C1) and 41(C1a) exhibited unevenly shaped fruits and were less circular. Large similarity and overlapping were noticed among accessions for fruit perimeter, fruit area, fruit width mid-height, maximum fruit width, fruit height mid-width and maximum fruit height. The foregoing corresponds to phenotypic plasticity in scarlet eggplant groups (Shippers, 2002; Adeniji et al., 2012, 2013), and other eggplant relatives (Kaushik et al., 2016). This is important for conservation and selection.

Table 5. The mean separation for some fruit size traits among accessions of the African eggplant (*Solanum aethiopicum*) group.

Accession code	Fruit perimeter	Area	Fruit width mid-height	Fruit maximum width	Fruit height mid-width	Fruit maximum height	Fruit curved height
1[a]	7.64l-p[b]	2.94i-l	2.02h-l	2.02l-r	0.86pq	1.21qr	2.14j-p
2	5.06t	1.93k-l	1.58j-m	1.57q-r	1.39l-p	1.37pqr	1.74o-q
3	8.04l-p	2.91h-l	1.93h-l	2.06l-r	0.35pq	0.65st	1.82opq
4	10.34f-i	1.34mn	1.26m	1.67o-t	1.49k-o	1.49n-r	4.70c
5	11.87de	8.70c	3.71bcd	3.70cde	2.80bcd	2.87b-e	3.12e-i
6	10.52e-h	4.91fgh	2.96d-g	2.94fgh	1.82g-l	1.88l-p	2.36i-o
7	16.12b	3.93g-j	2.45e-j	2.88f-i	1.47k-o	2.15g-l	4.58
8	8.18j-o	1.56mn	1.91h-l	2.02i-s	0.97op	1.10qrs	2.05l-p
9	48.3a	6.01ef	3.03c-g	4.57ab	2.72b-e	2.86cde	11.02a
10	20.5b	24.62a	3.90bc	3.94bc	7.52a	7.63a	7.75b
11	9.54i-j	2.52i-l	2.40e-j	2.67f-j	1.15m-p	1.39pqr	2.67g-m
12	8.22j-n	3.84g-k	3.17 c-f	2.41o-l	1.35l-p	1.69n-q	1.84o-q
13	8.12l-p	2.69i-l	2.41e-j	2.24l-p	1.16l-p	1.49n-r	2.06l-p
14	12.40d	11.66b	4.09ab	4.98a	3.22b	3.40b	3.76
15	6.80o	2.80i-l	1.89h-l	1.93o-t	1.43l-p	1.43o-r	1.47op
16	10.10ghi	6.18def	3.03c-g	3.05efg	2.46def	2.47e-i	2.90e-i
17	14.80c	1.50mn	4.98a	4.98a	0.27r	0.67st	2.41g-o
18	20.51b	25.31a	3.91bc	3.70cde	7.52a	7.62a	7.75b
19	11.73de	8.13cd	4.21ab	4.21bc	2.14e-i	2.34e-k	2.62f-n
20	10.09ghi	5.11fg	3.17bcd	3.22	1.72i-m	1.99 i-m	2.54f-o
21	7.86l-p	3.73g-k	2.40e-h	2.40g-l	1.55k-n	1.55n-r	1.05 l-p
22	8.19j-o	1.68lmn	1.25m	1.87o-t	1.06n-p	1.12rst	2.51 g-o
23	9.33h-k	3.64g-k	1.25m	2.57f-l	1.85i-l	1.93l-o	2.73f-l
24	7.30m-s	2.30j-l	1.87h-l	1.87o-t	1.79i-l	1.79l-p	2.00l-p
25	6.75p-s	2.60i-l	1.57j-m	1.57q-t	1.81i-l	1.83l-p	1.95l-q
26	9.31hijk	3.77g-k	3.03c-g	3.09efg	1.44l-o	1.44l-o	1.81m-p
27	5.98st	0.82n	2.20g-j	2.20l-r	0.33qr	0.33qr	0.61t
28	6.98n-s	2.83i-l	1.60j-m	1.60p-t	1.87g-l	1.87g-l	1.87l-p
29	11.64def	8.22c	3.83bcd	3.84cd	2.33d-h	2.33d-h	2.58e-h
30	8.23j-m	3.71g-k	2.28f-i	2.29l-q	1.64j-n	1.64j-n	1.69n-p
31	11.71def	8.57c	2.67e-g	2.69f-i	3.18bc	3.18bc	3.18bcd
32	7.52m-p	2.85i-l	1.73i-l	1.77o-t	2.51def	2.51def	2.67e-g
33	8.43jkl	3.72g-k	2.26g-i	2.32i-p	1.87g-l	1.87g-l	2.01i-n
34	7.17 m-s	8.21c	1.93h-l	2.12l-j	2.02f-k	2.02f-k	2.11h-m
35	6.20rst	2.25j-l	2.00h-l	2.02l-s	1.38l-p	1.38l-p	1.55n-r
36	9.27h-k	2.69i-l	1.50klm	1.64o-t	2.23d-j	2.23d-j	2.29f-j
37	10.98efg	7.32cde	2.24g-j	2.24l-p	3.27b	3.27b	3.27bc
38	7.51m-p	2.93t-l	1.39lm	1.51rst	2.5def	2.50def	2.71def
39	7.51m-p	2.93h-l	1.39lm	1.51rst	2.5def	2.50def	2.71def
40	6.98i-l	4.49f-i	2.03h-j	2.08l	2.63cde	2.63cde	2.79c-f
41	7.07m-s	2.39j-l	1.24m	1.31t	2.39e-g	2.39d-g	2.48e-j
42	7.99l-p	4.29f-i	2.53e-i	2.51g-l	2.04f-k	2.04f-k	2.14h-h

[a]refers to Table 1 for the accession name; [b]values in columns followed by the same letter are not significantly different.

Table 6. The mean separation for some fruit shape traits among accessions of the African eggplant (*Solanum aethiopicum*) group.

Accession code	Fruit shape eccentricity I	Fruit shape eccentricity II	Fruit shape index internal	Fruit eccentricity	Proximal eccentricity	Distal eccentricity	Fruit shape index external II	Lobeness
1[a]	0.56mn[b]	0.43opq	1.62bn	0.58l	0.89ab	0.86abc	0.42	10.28c-f
2	0.77i-m	0.77m-o	1.10g-m	0.79ab	0.89ab	0.87abc	0.78b-f	7.11i-m
3	0.27no	0.19pqr	0.67k-n	0.45m	0.99ab	0.81abc	0.18f	16.13ab
4	0.89h-l	0.89h-n	2.76a	0.79ab	0.89ab	0.88abc	2.49a	12.55c
5	0.77i-m	0.75m-0	0.85i-n	0.77a-e	0.88ab	0.87abc	0.75c-f	4.76nop
6	0.65klm	0.54mpo	1.90b-e	0.68g-k	0.88ab	0.89abc	0.53def	7.33g-l
7	0.68j-m	0.62l-o	0.81j-n	0.74a-h	0.88ab	0.88abc	0.62c-f	6.63k-n
8	0.68j-m	0.60mno	1.30d-l	0.68g-k	0.88ab	0.89abc	0.60c-f	6.80k-n
9	1.08g-j	1.02c-j	1.07i-m	0.78a-d	0.89ab	0.88abc	1.02b-f	6.80k-n
10	2.02a	2.06a	2.23ab	0.78a-d	0.87ab	0.87abc	2.07ab	17.98a
11	0.56mn	0.96f-j	0.63lmn	0.65 i-l	0.88ab	0.88abc	0.46ef	9.43f-h
12	0.58lmn	0.46opq	0.62lmn	0.59l	0.88ab	0.89abc	0.47ef	9.36f-i
13	0.85i-m	0.82h-o	1.07g-m	0.74a-i	0.88ab	0.87abc	0.82b-f	3.00opq
14	0.82i-m	0.78h-o	0.92k-m	0.76d-f	0.71cd	0.88abc	0.77c-f	3.91opq
15	0.71j-m	0.71j-o	0.74j-n	0.79ab	0.89ab	0.87abc	0.71c-f	7.70h-l
16	0.68j-m	0.77h-o	0.87k-n	0.71c-h	0.63jkl	0.87abc	0.73c-f	3.13pq
17	1.46cde	1.42c-e	1.47c-h	0.76 a-f	0.88ab	0.87abc	1.42	10.28c-f
18	1.91ab	1.92a	1.98bcd	0.78abc	0.88ab	0.73cd	1.93a-c	16.14ab
19	0.79i-m	0.73j-o	0.87k-n	0.70f-i	0.88ab	0.88abc	0.73c-f	9.09e-i
20	0.63klm	0.55m-p	0.87k-n	0.69f-i	0.89ab	0.82abc	0.55def	8.09f-l
21	0.64klm	0.68j-o	0.82i-n	0.79ab	0.89ab	0.87ab	0.84b-f	8.58e-i
22	0.60lm	0.56m-p	1.41d-h	0.72c-h	0.89ab	0.87ab	0.52def	8.38e-k
23	0.83i-m	0.79h-n	0.90l-r	0.75a-g	0.89ab	0.88ab	1.31a-f	4.25opq
24	0.82i-m	0.79h-o	0.93i-m	0.76a-f	0.89ab	0.78c	1.04b-f	4.15opq
25	1.16e-h	1.16d-h	1.25d-c	0.79ab	0.89ab	1.16a-f	1.16a-f	8.07f-l
26	0.58lmn	0.47opq	0.67lmn	0.63jkl	0.63jkl	0.88ab	0.47ef	9.15e-i
27	0.95h-k	1.06d-i	2.19abc	0.78a-d	0.78a-d	0.91a	1.06b-f	9.60
28	1.16e-h	1.16d-h	1.18c-l	0.80a	0.80a	0.88abc	1.17a-f	7.72h-l
29	0.67klm	0.60m-p	0.77j-n	0.71d-i	0.71d-i	0.88abc	0.60c-f	6.76k-n
30	0.86h-l	0.62l-o	1.13i-m	0.74a-h	0.74a-h	0.83abc	0.79b-f	4.87m-p
31	0.001h-l	0.01	0.79mn	0.80a	0.80a	0.89 abc	1.18a-f	7.72h-l
32	1.35def	1.35cdef	1.44d-i	0.79ab	0.79ab	0.89 abc	1.34a-f	10.02c-g
33	0.86h-l	0.82h-n	1.07i-m	0.74a-h	0.74a-h	0.88 abc	0.82b-f	3.39opq
34	1.06fgh	1.04e-j	1.24e-l	0.77a-e	0.77a-e	0.88 abc	1.04b-f	2.28q
35	0.76i-m	0.68j-o	0.87i-n	0.70f-i	0.70f-i	0.88 abc	0.68c-f	6.08l-o
36	1.39de	1.47bcd	1.85b-f	0.77a-e	0.77a-c	0.88 abc	1.46a-f	10.25c-f
37	1.46ced	1.46bcd	1.46c-h	0.80a	0.80a	0.89 abcd	1.47a-f	11.75cd
38	1.65bcd	1.73abc	1.86b-f	0.78a-d	0.78a-d	0.91a	1.74a-e	12.11c
39	1.78a-c	1.79ab	1.82b-g	0.73b-g	0.73b-h	0.88 abc	1.80a-d	14.78b
40	1.31efg	1.29d-g	1.56ghi	0.78a-d	0.78a-d	0.88 abc	1.33a-f	6.74k-n
41	1.89ab	1.92a	2.20ab	0.76a-f	0.76a-f	0.88 abc	1.72a-c	16.59ab
42	0.85h-m	0.81h-n	0.931j-m	0.75a-g	0.75a-g	0.88 abc	0.81b-j	3.93pq

[a]refers to Table 1 for the accession name; [b]values in columns followed by the same letter are not significantly different.

The CV (%) value < 20% is considered to be good, indicating the accuracy of the experiments (Table 7). These traits are relevant for characterization, documentation, conservation and crop improvement. It is essential to partition observed variability into genotypic, phenotypic and environmental effects for the selection of superior genotypes. This is important in determining the additive proportion of phenotypic variability. The variance due to the genotypic effect was low in magnitude, while the phenotypic variance was large (Table 7).

Table 7. Components of genetic variation and broad-sense heritability estimates for fruit metric and shape traits among the *Solanum aethiopicum* group.

Fruit metric trait	Coefficient of variation (%)	Genotypic variance	Phenotypic variance	Phenotypic coefficient of variation	Genotypic coefficient of variation	Broad-sense heritability
Fruit perimeter	4.72	46.07	69.02	45.47	33.70	67
Fruit area	14.06	12.73	25.80	100.70	99.70	49
Fruit width mid-height	12.71	0.85	0.92	39.0	38.0	92
Fruit maximum width	9.67	0.85	0.90	37.0	37.0	94
Fruit height mid-width	9.68	3.99	16.05	59	58	24
Fruit maximum height	8.25	1.90	1.93	62	61	98
Fruit curved height	8.29	3.30	3.38	62	61	98
Fruit shape index internal	15.03	0.03	0.03	39.0	39.0	100
Fruit shape eccentricity I	12.22	0.22	0.22	50.43	49.28	100
Fruit shape eccentricity II	14.00	0.23	0.25	54	53	92
Fruit eccentricity	3.28	0.004	0.009	12.82	11.31	44
Proximal eccentricity	5.71	0.002	0.004	22	16	50
Distal eccentricity	3.60	0.0005	0.0014	4.30	2.57	36
Fruit shape index external II	4.82	0.26	0.43	64.92	45.00	60
Lobeness	9.43	29.50	119.29	134.17	66.72	25

Values for genotypic and phenotypic variances were very close to or equal in magnitude for few traits. For all traits, the phenotypic coefficient of variation (PCV) was, in most cases, large compared to the genotypic coefficient of variation (GCV). The difference in magnitude between PCV and GCV was very close. Estimates of the coefficient of variation for phenotypes were low (distal eccentricity) and high (curved fruit height). The GCV values were not like PCV values, the maximum difference between the GCV and PCV was found in fruit lobes. Broad-sense heritability values were greater than 80% for fruit area, fruit width mid-height, fruit width (maximum), fruit height mid-width, fruit height (maximum), fruit curved height, fruit shape eccentricities I and II, and fruit lobes. A moderately low estimate for GCV for fruit metric traits implies that the improvement in this trait may be achieved to a reasonable extent. Low PCV and GCV values for fruit traits correspond to less phenotypic gain under selection. High PCV values indicate the extent of phenotypic improvement through selection to enhance the potentiality of fruit size. The difference between the PCV and the GCV was low for traits, inferring a low influence of environmental factors compared to genetic factors. In a separate study, the magnitude of GCV and PCV was close for fruit size in bell pepper (*Capsicum annuum* [L.]), another member of the Solanaceae, implying that the selection of fruit size will be worthwhile for the improvement in fruit yield (Sharma et al., 2013). Moderate to high variability for fruit yield indicated a possibility for the improvement through selection. Heritability values were moderately high for fruit curved height and low for lobeness, distal eccentricity and fruit mid-width. The magnitude of variability for fruit metric traits among scarlet eggplant groups is important for breeding, selection, and conservation. The phenotypic and genotypic coefficients of variation for all fruit metric characters indicate that the fruit metric traits are heritable.

The PC analysis indicated 4 of 15 PC axes had eigenvalues >1.3 and were responsible for most of the total variation among accession means (Table 8). The discriminating ability of eigenvalues was high for PC axes 1 and 2, which collectively explained most fruit metric variation. The first PC was frequently correlated with the large and elongated fruit. There were positive coefficients for fruit maximum height and height mid-width, fruit shape eccentricity I and fruit shape eccentricity II with equal loading, and fruit area. Distal eccentricity and proximal eccentricity had equal loading with negative coefficients on PC 1. The second PC axis had a high frequency of positive than negative eigen coefficients. Circular and curved fruit shapes predominate with positive coefficients (fruit shape index and curved fruit shape index), and these traits had negative coefficients on PC 1. Negative and equal coefficients occurred for fruit mid-width height and fruit maximum width. Traits associated with fruit size had negative coefficients on PC 2. The magnitude of variance concentrated in PCs 1 and 2 was attributed to fruit size and shape (maximum height, height mid-width, and area, curved width, fruit shape eccentricity I and fruit shape eccentricity II). These traits could form a focal point for characterization and conservation. Accessions with large-sized fruits are characterized by a low number of fruits per fruit cluster and total fruits harvested on an individual plant basis (Adeniji et al., 2012, 2013). Accessions 31 (C4) and 41 (C1a) were characterized by very small fruit size and preferred fruit taste. Accessions 9 (C3), 17 (Outlier) and 19 (C2b) are possible pollen sources for fruit width. Proximal and distal fruit end shapes are indicators of fruit size. Among members of the Gilo, the distal end of the fruit is pointed. The Kumba group is characterized by a depressed distal fruit end. Fruit end shape is important for packaging, ease of transportation over a long distance, and display in stores. Fruit shapes in the Gilo group are oval, pear-shaped and oblong. Fruits of the Kumba group are deeply lobed, less circular, furrowed and flattened compared to the Gilo group (Adeniji, 2013; Plazas et al., 2014), and fruits of the Shum group are circular. Accessions of the Kumba group are more lobed compared to the Shum group accessions, and the latter are more uniform and ovoid. Traits with eigenvectors greater than >0.25 are important contributors to the variation observed for PC 1.

Table 8. Eigenvalues and vectors, correlation coefficients of fruit phenomic traits for the first four principal component axes.

Variable	PC 1	PC 2	PC 3	PC 4
Fruit perimeter	0.24	-0.22	0.40	0.28
Fruit area	0.35	-0.15	-0.14	-0.07
Fruit width mid-height	0.19	-0.40	-0.16	-0.11
Fruit maximum width	0.19	-0.40	0.26	-0.04
Fruit height mid-width	0.37	-0.02	-0.15	-0.007
Fruit maximum height	0.37	-0.04	0.12	-0.03
Fruit curved height	0.29	-0.10	0.30	0.03
Fruit shape eccentricity I	0.26	0.33	0.17	-0.29
Fruit shape eccentricity II	0.26	0.34	0.16	-0.25
Fruit shape index internal	0.13	0.40	0.08	0.14
Fruit eccentricity	0.12	0.19	-0.05	0.43
Fruit proximal eccentricity	-0.27	0.08	0.39	0.13
Fruit distal eccentricity	-0.27	0.04	0.41	0.08
Fruit shape index external II	0.11	0.27	0.02	0.48
Fruit lobeness	0.22	0.23	0.05	0.01
Eigenvalue	6.12	3.18	1.62	1.34
Proportion	0.38	0.20	0.10	0.08
Cumulative (%)	38	58	68	77

The projection of accessions on a 2-dimensional plot of principal component axes 1 by 2 (Figure 1) indicated the spread of accessions into 4 quadrants alongside traits responsible for ordination. Fruits of accessions ordered in quadrant 1 are circular and curved with oval seed shape (positive coefficients on PCs 1 and 2 for fruit shape eccentricities I and II, fruit curved height, fruit shape index and lobeness) (Figure 1). Accession 10 (Q1) was widely separated from others, indicating the highest contribution to phenotypic variability in this quadrant.

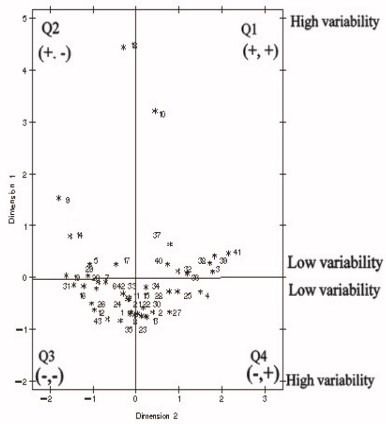

Figure 1. The ordination of 43 accessions from the *Solanum aethiopicum* group derived from the unweighted pair group method of analysis clustering of correlation coefficients for 15 phenomic traits by the squared Euclidean distance and the Ward's method.

Q1 (Quadrant 1) PC1: PC2 (+, + coefficients), Q2 (Quadrant 2) PC1: PC2 (+, - coefficients), Q3 (Quadrant 3) PC1: PC2 (-, - coefficients), Q4 (Quadrant 4) PC1: PC2 (+, - coefficients).

Entries in the second quadrant were characterized by the large, elongated fruit with positive and negative coefficients on PCs 1 and 2 (fruit height mid-width, fruit maximum width, fruit width mid-height, fruit maximum height, fruit curved height, fruit area and fruit perimeter). Accession 18 (Q2) was widely separated from other entries in the second quadrant. Accessions 18 (Q2) had the highest contribution to fruit metric variability, followed by Accession 9 (Q2). The ordination of entries in the third quadrant is consistent with differences in fruit distal end blockiness, with negative coefficients on both PCs 1 and 2. Fruits that are more triangular, less ellipsoidal and circular, round, and pear-shaped predominate in this quadrant. Ten accessions were dispersed in the fourth quadrant, with traits associated with this dispersion being proximal and distal eccentricity, fruit area index, with negative and positive coefficients, on PCs 1 and 2. No accession was dispersed in the top right and left-hand corner of quadrants 1 and 2, with a maximum contribution to fruit metric variability.

The dendrogram grouped the scarlet eggplant accessions into 4 clusters (C_1, C_2, C_3 and C_4) (Figure 2). The first cluster (C1) was divided into sub-cluster 'a' with 9 accessions and 5 accessions in sub-cluster 'b'. Accessions in the Gilo group predominate in this cluster, they were widely distributed in the first quadrant, with positive correlation coefficients on the plot of principal component axes 1 and 2. Cluster members were related by fruit shape eccentricity I, fruit shape eccentricity II, curved fruit shape 1, and fruit shape index and fruit lobes. Accessions ordered in cluster 1b were dispersed in quadrants 2 and 3 (Figure 1). Accessions of the Kumba group predominate in this cluster, they are triangular and lobed, less circular, flattened fruit (high values for fruit shape eccentricity indices I and II). Nine accessions were grouped in cluster 2 (C_2) and divided into sub-clusters 'a' and 'b'. Accessions of the Gilo group were interspersed among the Kumba group. This cluster had moderate fruit size (moderate values for fruit perimeter, fruit area, fruit mid-width height, fruit maximum height), and moderately lobed compared to clusters 1 and 4, and fruits are less ovoid and triangular. Moderate values for fruit shape eccentricity indices I and II compared to entries grouped in cluster 1 indicate a preponderance of accessions of the Gilo group in this cluster. Seven accessions among the Gilo and Kumba were grouped in cluster 3. Members of this group are characterized by medium and small fruit sizes (low values for fruit perimeter, fruit area, fruit width mid-height, maximum fruit width, fruit height mid-width) and short fruit. Accessions 24 and 27 (C3a) had small-sized fruits, accessions 30 and 42 (C3b) were oval, and accessions 6 and 14 (C3b) had medium-sized fruits. Members of cluster 3 were less circular (moderately high circular values), fairly lobed compared to clusters 1 and 4. Accessions grouped in cluster 4 were characterized by small fruit compared to clusters 1, 2 and 3. Accessions in cluster 4 had low to moderate fruit perimeter, fruit area and highly lobed fruit. Accessions 31 and 36 (C4) were related to fruit pericarp curvature. Dispersion of accessions on the PC plot is consistent with the grouping of accessions on the dendrogram. Accessions grouped in cluster 1 were dispersed in quadrants 1 and 4. Members of cluster 2 were ordered in quadrants 2 and 3, members of cluster 3 occurred in quadrants 2 and 3. Accessions in cluster 4 were dispersed in quadrants 1, 2, and 3. The out-group (accessions 4, 3 and 17 linked C4 at the lower end) were dispersed in quadrants 1, 4 and 2, respectively. A large number of traits needed to explain total variance for fruit metrics may be associated with duplicate accessions in the germplasm collection (Yada et al., 2010). Phenotypic improvement in fruit perimeter will account for large fruit size. Selection in favor of the fruit area will complement fruit eccentricity (proximal and distal). Accessions with a thick fruit will have a tall fruit shoulder.

The dispersion and ordination (Figure 1), and grouping of the accessions (Figure 2) in the dendrogram (Figure 2) indicate that members of Gilo and Kumba groups displayed fruit traits specific to each group which overlapped. Findings are similar to previous reports of Polignano et al. (2010) and Tümbilen et al. (2011). Accessions from different geographical locations grouped with other entries exhibiting geographic heterogeneity and fruit traits are not specifically assigned to a specific location. The dendrogram indicated 4 distinct clusters with overlapping and plasticity of fruit metric traits and geographical heterogeneity within and among clusters. The high degree of fruit metric variation and overlapping of fruit metric traits may be associated with ecological regions where accessions were collected. The proximity between Gilo and Shum groups confirm the findings of Shippers (2002) that the Gilo group evolved from the Shum group or that both share a common genome (Polignano et al., 2010; Plazas et al., 2014; Kaushik et al., 2016). A high degree of fruit metric trait diversity observed in the scarlet eggplant genetic resources necessitates conservation strategies for preserving local genetic resources for breeding (Polignano et al., 2010; Tümbilen et al., 2011; Plazas et al., 2014; Kaushik et al., 2016).

Conclusion

The range of variation was high in fruit perimeter, fruit lobeness, fruit curve height, fruit shape index, fruit maximum height, fruit maximum width, and fruit area. These traits are relevant for characterization, documentation, conservation and crop improvement. Broad-sense heritability values were greater than 80% for fruit area, fruit width mid-height, fruit width (maximum), fruit height mid-width, fruit height (maximum), fruit curved height, fruit shape eccentricities I and II, and fruit lobes. The dendrogram and PC plot grouped accessions by shape, size and fruit area. Accessions 9 (C3), 10 (C1) and 18 (C2) could be pollen parents for the improvement in fruit size through intraspecies hybridization within Gilo, between Gilo and Shum, and Gilo and Kumba groups. Using variation present in the eggplant materials, selecting and developing new varieties should be possible. The Tomato Analyzer software characterizes the fruits of scarlet eggplant by groups, and the information could be used to establish commonalities between groups.

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METRIČKA KARAKTERIZACIJA OSOBINA PLODA GRIMIZNOG PLAVOG PATLIDŽANA KORIŠĆENJEM VISOKOPROPUSNOG SOFTVERA ZA ANALIZU PARADAJZA

Olawale Taiwo Adeniji[1*], Modinat Adekoya[2], Peter Jonah[3], Innocent Iseghohi[1] i Charity Aremu[4]

[1]Odsek za ratarstvo i hortikulturu, Federalni univerzitet Oye Ekiti, Nigerija
[2]Odsek za nauku o biljkama i biotehnologiju,
Federalni univerzitet Oye Ekiti, Nigerija
[3]Odsek za ratarstvo, Državni univerzitet Adamava, Mubi, Nigerija
[4]Odsek za proizvodnju useva, Univerzitet Landmark,
Omuaran, Država Kvara, Nigerija

R e z i m e

Grimizni plavi patlidžan (*Solanum aethiopicum* [L.]) je autohtono, nedovoljno iskorišćeno plodovito povrće u Africi. Sklonost ka obliku i veličini ploda velika je među uzgajivačima i potrošačima. Metričke osobine ploda važne su za poboljšanje prinosa. Metrički deskriptori ploda značajno doprinose varijacijama, fenotipskim i genotipskim varijacijama i heritabilnosti. Međutim, merenje ovih osobina je komplikovano i subjektivno. Četrdeset i tri genotipa procenjena su u 2016. i 2017. godini. U fazi zrelosti, iz svakog genotipa nasumično je ubrano 5 plodova, digitalizovano i obrađeno pomoću softvera za analizu paradajza. Šesnaest metričkih osobina ploda automatski je generisano i dostavljeno za analizu varijanse i multivarijantnu analizu. Genotipovi su se razlikovali u odnosu na veličinu i oblik ploda zbog genetske predispozicije. Varijacija metričkih osobina ploda među grupama *S. aethiopicum* bila je pod manjim uticajem okoline. Grupa sorte Gilo ima duguljaste plodove, plodovi grupe sorte Shum su kružni i okruglasti; plodovi grupe sorte Kumba su manje kružni, režnjeviti i spljošteni. Grupe AE/113 (C3), FUO 1 (C1) i FUO 5 (C2) Gilo obećavajuće su za veličinu ploda. Postojala je fenotipska plastičnost i preklapanje za metričke osobine ploda između grupa Gilo i Shum zbog zajedničkog genoma. Softver za analizu paradajza je uspeo da razdvoji genotipove na osnovu fenotipskih osobina ploda, a informacije su mogle da se koriste za utvrđivanje zajedničkih osobina između grupa.

Ključne reči: *Solanum aethiopicum*, površina ploda, veličina ploda, genetski diverzitet, naslednost.

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[*]Corresponding author: e-mail: olawale.adeniji@fuoye.edu.ng