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RESEARCH PAPER

Investigating Phenotypic Diversity in a Germplasm Collection of Scarlet Eggplant under Mediterranean Conditions

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Abstract

This study aimed to determine phenotypic diversity in the germplasm collection of *Solanum aethiopicum*, also known as scarlet eggplant, under Mediterranean conditions. Two different experiments were established in which morphological and valuable agronomic traits were employed to measure diversity among 57 and 55 accessions, respectively. The experiments were carried out in a greenhouse and open field, and descriptors designated by the European Cooperative Program for Plant Genetic Resources (ECPGR) and the International Board for Plant Genetic Resources (IBPGR) were used to measure the plants and fruits. The results from descriptive statistics on quantitative traits data of plants and fruits show a great variation among accessions of *Solanum aethiopicum*. Multiple correlation analysis in the two distinct experiments shows that the highly correlated variables/descriptors represented fruit quantitative traits. Finally, results from principal component analysis (PCA) confirm that the overall differences observed in the germplasm collection of *Solanum aethiopicum* were mainly due to fruit quantitative traits, which are decisive for phenotypic characterization of this eggplant.

1. Introduction

Scarlet eggplant is often described as African eggplant. However, African eggplant is recognized as a large group in which African native eggplants such as gboma eggplant (*Solanum macrocarpon* L.) as well as scarlet eggplant (*Solanum aethiopicum* L.) are comprised as well as their wild ancestors (*Solanum dasyphyllum* and *Solanum anguivi*), respectively. In African cuisine, African eggplants are appreciated mainly for their edible fruits and sometimes for their leaves (Haliński et al., 2017; Mibei et al., 2018). Furthermore, they are commercially significant, and they are particularly popular among Sub-Saharan African smallholder farmers since they are effortless to grow with minimal inputs and are altogether matched to the local environment (Weller et al., 2015; Sseremba, 2019).

Scarlet eggplant (*Solanum aethiopicum* L.), broadly acknowledged as the other cultivated eggplant, is a near relative of Brinjal eggplant (*Solanum melongena*) and one of its direct wild ancestors is *Solanum anguivi*. Furthermore, a wide number of wild relatives of Brinjal eggplant are found on the African continent (Knapp et al., 2013; Knapp et al., 2019). Scarlet eggplant is a diploid with 24 chromosomes (2n = 24) and also part of the genus *Solanum* (Shimira et al., 2021). The genus *Solanum* is vast and prosperous in species. About 1400 species are approximately estimated to exist in this rich genus. Thirteen principal clades exist within the genus such as the spiny solanums, the Leptostemonum clade and the Potato clade (which comprises of potato and tomato) just to name a few.

The scarlet eggplant (*S. aethiopicum* L.) is part of the “Anguivi clade” (Knapp et al., 2013; Knapp et al., 2019). Scarlet eggplant is described as an herbaceous shrub with glabrous or hairy leaves. It is distinguished by its hermaphroditic flowers that grow in clusters or separately and these flowers are self- or cross-pollinated (Kamga et al., 2015). Scarlet and gboma eggplants are essentially cultivated and grown on the African continent, while the common eggplant is omnipresent globally; including Africa, Asia, subtropics (Central America, India) and in tempered regions like Mediterranean and southern USA (Gramazio et al., 2016; Zhuang et al., 2012). Apart from West and Central Africa, *S. aethiopicum* is also present in Caribbean countries, Brazil as well as South Italy. Africa is homeland to a great variety of wild relatives of the common eggplant (*Solanum melongena* L.) (Knapp et al., 2013; Gramazio et al., 2016).

Like common eggplant (brinjal), scarlet eggplant (*Solanum aethiopicum* L.*)* is consumed raw, boiled and/or fried, and also as an ingredient in stew and soup (Eletta et al., 2017). Their bitter taste is praised in their leaves and fruits. To a great extent, this may be due to the occurrence of alkaloids (mainly glycolalkaloids and phenolic compounds) establishing their edibility. In sub-Saharan Africa, leaves are consumed as vegetables, particularly leaves of the *S. aethiopicum* Kumba and Shum groups, ones of the four groups that make up *Solanum aethiopicum*. Consumers' preference for fresh fruit relies on a few quality traits such as fruit acidity and taste, fruit color, and phenolic contents in fruit and fruit epidermis (Adeniji et al., 2012).

There is mounting evidence that eating its leaves and fruits decreases the occurrence of chronic diseases such as diabetes and atherosclerosis (Mibei et al., 2018). The common eggplant (*Solanum melongena*) fruits have been used for the treatment of different diseases such as asthma, arthritis, bronchitis, and diabetes, as well as its nutritional features is valuable to the human diet (Foo et al., 2018). In the same manner, the African eggplant *Solanum aethiopicum* and *Solanum macrocarpon* have been used in traditional medicine in the cure of allergic rhinitis, asthma, constipation, dyspepsia, gastro-esophageal reflux disease, nasal catarrh, rheumatic disease, skin infections, and swollen joint pains. They are also used in weight reduction (Eletta et al., 2017). Furthermore, Kamga et al. (2015) have stated that the fruit from the three edible groups (Gilo, Kumba, and Shum) may accommodate up to 2% potassium, 10% protein, 80% water, high levels of antioxidant compounds, and carotenoids. It has been also reported by Kamga et al. (2013) that the Oforiwa variety of *Solanum aethiopicum* (originated from Ghana) contains a higher amount of carotenoids compared to other *S. aethiopicum* eggplant varieties originated from Ghana.

A small number of studies on the scarlet eggplant (*Solanum aethiopicum L.*) have been conducted in Africa and in Rwanda in particular. According to reports, eggplants are Rwanda's fifth most produced vegetable after cabbages, tomatoes, fresh beans, and squashes. Additionally, they are grown under the mixed agricultural practice that characterizes vegetable cultivation throughout the country, and most of the time on limited plots (Larochelle and Alwang, 2014; Van Dijk and Elings, 2014; Prasad et al., 2016). Eggplants are cultivated from commercial seeds accessible in the country, and their aspect is generally mediocre (Van Dijk and Elings, 2014). The hybrid seed market remains modest, and the seed types offered are insufficient. A few private companies sell open-pollinated varieties at reasonable prices in various franchise shops across the country (Dijkxhoorn et al., 2016; Uwamahoro et al., 2020).

The informal seed sector is dominant in Rwanda, with farmers primarily using saved seeds. Adoption of enhanced crop varieties is relatively moderate, with only a few breeding lines and improved varieties of African eggplant documented. Maize is an exception, with high adoption of hybrids. The Rwanda Agriculture Board primarily produces breeds and pre-basic seeds of crops such as maize, beans, rice, and wheat. National breeding programs focus on economically important crops such as sweet potatoes, cassava, and common beans, with a focus on developing pest and virus-resistant varieties through marker-assisted selection. As well as potato clones crops resulting from crosses between local and foreign varieties have been released in the country (Gapusi et al., 2013; Larochelle and Alwang, 2014; Context Network, 2016; Mujuju, 2018; Dusengemungu et al., 2019; Shimira et al., 2020). No African eggplant varieties or seed products have been released by national agricultural research institutions since 1990, with all available varieties being open-pollinated (Schreinemachers et al., 2017).

Globally, substantial investigations and breeding programs have been conducted on brinjal (*Solanum melongena* L.) and, to a lesser extent, on its related species such as *Solanum americanum*, *Solanum incanum*, and *Solanum torvum* (Isshiki et al., 1998; Caguiat and Hautea, 2014). This condition dragged scarlet eggplant (*Solanum aethiopicum* L.) and relatives (close and/or wild) into the category of "orphan crops" or underappreciated crops, along with a great number of other African indigenous vegetables (Kamga et al., 2015; Weller et al., 2015; Song et al., 2019). Scarlet eggplant, along with *Solanum incanum*, is acknowledged as a desirable provenance of variations in *Solanum melongena* breeding schemes, and it has also been revealed as cross-compatible with *Solanum melongena* (Gramazio et al., 2016). In brief, due to environmental changes in recent years, there is in breeding programs an enthusiasm for crop wild relatives (CWR) of agronomically important crops. These taxa have wide-raging relationships and identities (Knapp et al., 2013).

Within the *Solanum aethiopicum* species, four cultivar groups were identified based on morphological characteristics: Gilo, Aculeatum, Kumba, and Shum. Thus, the Gilo group is by far the most significant of these groups, and it is appreciated for its tasty oval to spherical fruits (Osei et al., 2010; Adeniji et al., 2012; Kamga et al., 2015; Gramazio et al., 2016; Haliński et al., 2017). The only group that is not edible is the Acelatum group (Kamga et al. 2015). As also described by Lester and Daunay (2003), different shapes and sizes of fruits and leaves subsist within the four cultivars of *Solanum aethiopicum*.

Smallholder farmers' ability to grow and realize benefits from scarlet eggplant and other African indigenous vegetables (AIVs) is limited by a scarcity of high-quality seeds. Additionally, attempts to assist AIVs are impeded by an absence of breeding, genetics, and market demand research (Kansiime et al., 2018). A few number of investigations on the scarlet eggplant (*Solanum aethiopicum* L.) have been conducted in Rwanda. As a case in point, Adeniji et al. (2012) employed one accession of the *Solanum aethiopicum* Gilo group from Rwanda in a phenotypic diversity research with 43 other scarlet eggplant accessions from Africa, Europe, Asia, and South America (inclusive of all four groups: Gilo, Shum, Kumba, and Aculeatum). Similarly, in a morphological characterization research of gboma eggplant, scarlet eggplant, and wild related (*Solanum anguivi*) accessions from five additional African nations, Kamga et al. (2015) employed three Rwandan scarlet eggplant accessions.

During the domestication of *Solanum aethiopicum* from its ancestral parent, *Solanum anguivi*, distinctive gains or morphological diversity have been recorded. Changes in leaf sizes and shapes from broad, deeply lobed, hairy, prickly, shrubs, perennial plant and spherical fruit (1 cm diam.) to smaller, less lobed leaves, glabrous, non-prickly, herbs, annual plants and different shaped and sized fruit. Obtained cultigens resulting from domestication of *Solanum aethiopicum* displays different morphological features with their ancestor and within themselves (Lester and Daunay, 2003). This morphological divergence was also confirmed by Adeniji et al. (2012) when they carried out diversity examination among the *Solanum aethiopicum* groups. Higher divergence was reported in different accessions within the Gilo, Aculeatum, and Kumba groups than between groups themselves. However, a little difference (minimum diversity) has been perceived when analyzing molecular markers, essentially isozymes and DNA between cultigens (Lester and Daunay, 2003).

In brief, the intent of this study is to investigate the phenotypic diversity of scarlet eggplant under Mediterranean conditions. This will be achieved through the determination of the morphological diversity of several eggplant accessions originated from Rwanda using several descriptors of Solanaceae and eggplants. Additionally, the study aims to select and recommend ideal and high-potential accessions for future breeding programs. By understanding the diversity within this eggplant variety, we hope to contribute to the improvement of eggplant breeding and cultivation in Mediterranean regions.

2. Material and Methods

2.1. Plant materials

For the purpose of this research study, different experimental fields (open-field, and greenhouses) were used to establish an eggplant germplasm field in Türkiye (Table 1) from seeds originally collected from two distinct districts (Gakenke and Musanze) of Rwanda (Shimira et al., 2021). Experimental fields were set up depending on the targeted specific morphologic experiments and the growing seasons (2020-2021, and 2022).

At each experimental field site, seed germination and propagation were carried out by sowing eggplant seeds from all 60 different accessions in plant growing trays (4 × 6 cells each) containing a mixture of peat and perlite (3:1, w/w). Four different eggplant accessions were sown on each plant's growing tray. The temperature in the greenhouse was kept at 25°C during the germination period, and the plant growing trays were frequently irrigated. Unfortunately, due to the poor quality of some seeds, all accessions did not develop as expected. Depending on the experimental sites and growing seasons, between 55 and 57 accessions germinated successfully.

2.2. Experimental design and plantlets transfer to the fields

In the seventh week after seed sowing and germination, well-grown eggplant plantlets were transferred from plant growing trays into a well-prepared and designated experimental field bed with natural soil. Plants were cultivated in a completely randomized block design, with three replications of each accession arranged within eight

Table 1. Location of experimental fields in Antalya (Türkiye).

N°	Institution	GPS coordinates	Types of cultivation	Growing season
1	Batı Akdeniz Agricultural Research Institute (BATEM) - Department of Vegetable Crops and Ornamentals.	36°55'45.7"N 30°58'47.3"E	Greenhouse	2020-2021
2	Fidesan Fide Ltd.	36°54'38.0"N 30°58'25.8"E	Open field	2022

rows. The spacing between rows was approximately 1.4 m, and the spacing within rows was approximately 0.75 m. Water soluble fertilizers such as potassium nitrate (13-0-46), Mono-ammonium phosphate (12-61-0), and Urea were applied to the plants once a week. Drip irrigation was adopted, and irrigation is always performed on a regular basis to maintain soil moisture. Weeds were also thoroughly removed once per week. Other agronomic management practices were carried out, such as systematic pruning for each plant and application of chemicals in order to manage pests (Spider mite, *Tuta absoluta*, whitefly) and diseases (powdery mildew and botrytis).

Experiments of morphological characterization were both carried out in Antalya (Türkiye). The greenhouse experiment of agro-morphological characterization was performed at the BATEM Institute in spring-autumn from June 2020 to January 2021. The experimental field was 0.32 da and plant pruning was also carried out. The open field experiment of agro-morphological characterization was carried out in a field belonging to a private company (Fidesan Fide Ltd.) in spring-autumn from March 2022 to July 2022 (Figure 1). The experimental field in this case was also 0.32 da, however, there was no pruning carried out during this experiment.

2.3. Morphological variation analysis

The morphological and agronomic valuable traits assessed were mainly based on two distinct descriptors with some modifications. Those descriptors were both advanced by the European Cooperative Programme for Plant Genetic Resources (ECPGR) and the International Board for Plant Genetic Resources (IBPGR) for *Solanaceae* and eggplant, respectively (Boyaci et al., 2020). Measurements on plant agronomic, qualitative, and quantitative traits (leaf prickliness, leaf hairiness, corolla color, plant height, etc.) were gathered according to replications. Similarly, fruit qualitative and quantitative traits (fruit color, length, weight, width, etc.) were measured using 3 ripened fruits (commercial stage) per replication of each accession. The used morphological and agronomically important traits are listed in Table 2, Table 3, and Table 4. Additionally, Figure 2, Figure 3, Figure 4, Figure 5 depict the work flow of agro-morphological characterization.

2.4. Multivariate analysis of morphological relationship

Relationship analysis was carried out on morphological traits data from two distinct growing seasons (2020 and 2022) by employing JMP software (version 15.2.1, SAS Inc., Cary, NC, USA). Furthermore, inter-trait correlations, principal component (PCA) and cluster analyses were determined by using the same software.

3. Results and Discussion

A perceptible level of phenotypic variations has been recorded from *Solanum aethiopicum* gr. Gilo germplasm in three distinct experiments with reference to measured morphological and valuable agronomic traits.

3.1. The greenhouse experiment (I)

A summary of the descriptive statistics (means, standard deviations, and maximum and minimum values) for the greenhouse experiment conducted in 2020 is shown in Table 5.

Descriptive analyses made from the data of quantitative traits of plants and fruits displayed a wide range of variations among all 57 accessions of *Solanum aethiopicum* gr. Gilo. For instance, the minimum leaf blade width was 14.7 cm (for accession MZE37) and the maximum was 31.7 cm (for accession MZE31); leaf blade length ranged from 24.0 cm (for accession MZE34) to 40.5 cm (for accession GKE14); and total plant height was scaled from 70.0 cm (for MZE27) to 240.0 cm (for GKE21).

Besides, we also noted extent changes from fruits' qualitative traits on studied accessions. As an illustration, fruit weight ranged from 10 g (for

Figure 1. Open field at Fidesan Fide Ltd. (A) During plantlets plantation (May 2022), (B) During fruits harvesting (end July 2022).

Table 2. List of descriptors employed for plant qualitative and quantitative traits.

Morphological descriptor	Abbrev.	Scale/Unit	Description
Growth habit	GHA	[1-7] >> *1=very upright, 3=upright, 5=intermediate, 7=prostrate*	
Leaf blade lobes	LBO	[1-7] >> *1=very weak, 3= weak, 5=intermediate, 7=strong,9=very strong*	
Anthocyanin distribution in plant	ADP	[1-7] >> *1=absent, 3=low, 5=intermediate, 7=high*	General anthocyanin distribution in apex, stem, calyx, prickles, leaf veins
Anthocyanin distribution in leaves	ADL	[1-7] >> *1=absent, 3=low, 5=intermediate, 7=high*	Anthocyanin distribution in leaf blade (intervein) as many times is different from the other tissues
Leaf prickliness	LPR	[0-9] >> *0=none, 1=very few (1-2), 3=few (3-5), 5=intermediate (5-10), 7= many (11-20), 9= very many (>20)*	3 representative fully expanded leaves.
Leaf hairiness	LHA	[0-5] >> *0=none, 1= low, 3=intermediate, 5=high*	3 representative fully expanded leaves.
Corolla color	CCO	[0-10] >> *0=yellow, 1=green, 2=greenish white, 3=white, 4=rose, 5=pink, 6=dark pink, 7=pale violet, 8= violet, 9=dark violet ,10=blue*	
Fruit load	FLO	[0-9] >> *0= none, 1=very low, 3=low, 5=intermediate, 7=high, 9=very high*	
Stem color	SCO	[1-5] >> *1=green, 3=greenish purple, 5=purple,*	Measured in 3 representative fully expanded leaves.
Petal color	PCO	[1-5] >> *1=green, 3=greenish purple, 5=purple.*	Measured in 3 representative fully expanded leaves.
Leaf blade width	LBW	Cm	Measured in 3 representative fully expanded leaves)
Leaf blade length	LBL	Cm	Measured in 3 representative fully expanded leaves)
Total plant height	TPH	Cm	Measured in the principal stem at the end of cropping period. Average of 2 plants per rep/accession

Table 3. List of Descriptors employed for fruit qualitative traits.

Morphological descriptor	Abbrev.	Scale/Unit	Description
Varietal type	VTY	[1-7] >> *1=long, 3=oval, 5=round, 7=striped.*	According to local description already existing
Predominant fruit color	PFC	[0-10] >> *0=dark green, 1=green, 2=milk white, 3=deep yellow, 4=fire red, 5= scarlet red, 6= lilac, 7= dark lilac, 8=purple.*	
Secondary fruit color	SFC	[0-10] >> *0=dark green, 1=green, 2=milk white, 3=deep yellow, 4=fire red, 5= scarlet red, 6= lilac, 7= dark lilac, 8= purple, 9=dark purple, 10=black.*	
Fruit color distribution	FCD	[1-7] >> *1=uniform, 3=mottled, 5=netted, 7=striped*	
Fruit undercalyx colour	FUC	[0-2] >> *0= absent, 1= intermediate, 2=present*	Presence of a lighter peel color edge next to calyx
Fruit glossiness	FGL	[1-3] >> *1=opaque, 2=intermediate, 3=bright peel color*	3 representative fruits /block/ accession
Fruit curvature	FCU	[0-9] >> *0=round, 1=no curvature, 3=slightly curved, 5=curved, 7=S shaped, 9= U shaped*	3 representative fruits /block/ accession
Fruit apex shape	FAS	[3-7] >> *3= protruding, 5=smooth, 7=depressed*	3 representative fruits /block/ accession
Position of the maximum diameter	PMD	[2-8] >> *3= about ¼ way from base to tip, 5= about ½ way from base to tip, 7= about ¾ way from base to tip*	3 representative fruits /block/ accession
Fruit cross section	FCS	[1-7] *1=circular, 3=elliptic, 5=smashed, 7=very irregular*	3 representative fruits /block/ accession
Presence of grooves on fruit	PGF	[1-3] >> *1=absent, 3=present*	
Presence of hole in fruit	PHF	[1-3] >> *1=absent, 3=present*	
Fruit end button size	FEB	[0-3] >> *0=none, 1=small, 2=intermediate, 3=large*	
Fruit shape	FSH	[1-9] >> *1=broader than long, 3=as long as broad, 5=Slightly longer than broad, 7=Twice as long as broad, 8=Three time as long as broad, 9=several times as long as broad*	
Presence of clorophyll on the pistil scar	PCP	[1-3] >> *1=absent, 3=present*	
Seed content	SEC	[1-3] >> *1=absent, 3=present*	

Table 4. List of descriptors employed for fruit qualitative and quantitative traits.

Morphological descriptor	Abbrev.	Scale/Unit	Description
Fruit weight	FWE	g	
Fruit length	FLE	Cm	
Fruit maximum diameter	FMD	Cm	
Peduncle length	PLE	Cm	
Fruit calyx prickliness	FCP	[0-9] >> 0=none, 1=Very few (<3), 3=Few (~5), 5=Intermediate (~10), 7=Many (~20), 9= Very many (>30)	Average of 3 values/block
Calyx fruit coverage	CFC	[1-5] >> 1= less than 10%, 2=10-20%, 3=20-30%, 4=30-40%, 5=50% and more	Average of 3 values/block
Locule number	LON	Count	Average of 3 values/block
Presence of a greenish ring next to the peel	PGP	[0-2] >> 0=no, 1= slight, 2=yes and markedly green	Average of 3 values/block
Average color of the flesh	ACF	[1-7] >> 1=white, 3=greenish, 5=green, 7=cream	Average of 3 values/block

Figure 2. Steps of morphological analysis (A) & (B) Fruit samples collection in the open field of Fidesan Fide Ltd. (Antalya – July 2022), (C) Fruit samples after collection.

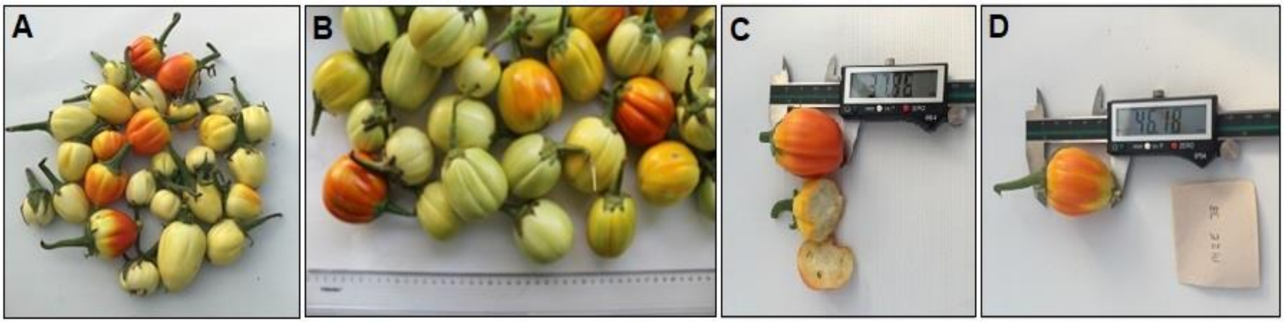

Figure 3. Fruit samples collected in greenhouse of BATEM Institute (January 2021) (A) Fruits presentation, (B) Fruits presentation next to a ruler, (C) Fruit height measurement with digital caliper and transverse section of fruit, (D) Fruit height measurement with digital caliper.

Figure 4. Fruit samples collected in Antalya – July 2022 (Fidesan Fide Ltd.).

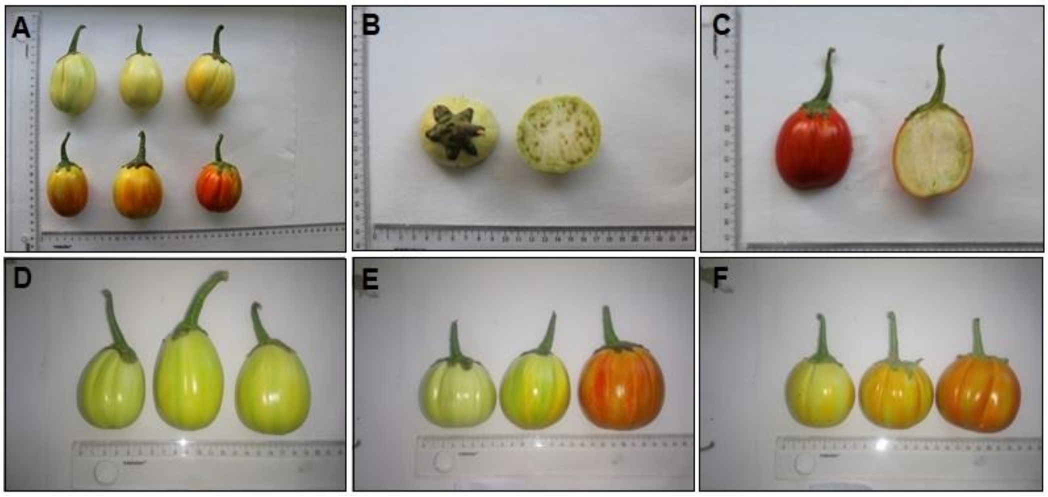

Figure 5. Fruit samples display (A) Fruits presentation, (B) Transverse section of fruit, (C) Longitudinal section of fruit (D) GKE7 fruit samples, (E) MZE49 fruit samples, (F) MZE47 fruit samples.

Table 5. Descriptive statistic summary for the studied quantitative variables in the greenhouse experiment.

Trait category	Descriptor abbreviations	Mean	STD	Range	
				Min	Max
Qualitative traits of plant	LBW	23.51	3.59	14.75	31.75
	LBL	32.63	3.41	24.00	40.50
	TPH	139.29	39.28	70.00	240.00
Quantitative traits of fruit	FWE	25.75	9.53	10.00	45.00
	FLE	4.01	0.77	2.60	5.57
	FMD	3.50	0.51	2.50	4.70
	PLE	3.61	0.61	2.25	4.90
	LON	5.85	1.37	3.00	9.00

Table 6. Correlation coefficient between descriptors in the greenhouse experiment.

Row	LBW	LBL	TPH	FWE	FLE	FMD	PLE	LON
LBW		0.612	0.026	0.249	0.018	0.293	-0.311	0.183
LBL			0.368	0.542	0.240	0.467	-0.031	0.077
TPH				0.339	0.221	0.281	0.157	0.109
FWE					0.801	0.937	0.588	0.336
FLE						0.741	0.616	0.262
FMD							0.554	0.423
PLE								0.198
LON								

LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number

accession GKE11) to 45 g (for accession MZE41), fruit length ranged from 2.6 cm (for accession MZE51) to 5.6 cm (for accession MZE53), fruit maximum diameter ranged from 2.5 cm (for accession MZE36) to 4.7 cm (for accession MZE41), peduncle length ranged from 2.3 cm (for accession MZE57) to 4.9 cm (for accessions MZE53 and MZE48), and locule number ranged from 3 (for accession GKE20) to 9 (for accession MZE53).

The statistical correlation test between all 8 studied quantitative traits showed corresponding correlation coefficients in Table 6. It was found that both positive and negative correlations prevail among morphological and agricultural valuable traits.

The correlation coefficient r values were all significant at $P < 0.05$. For instance, more positive significant correlation coefficients (values above 0.6) are listed as follow: fruit weight (FWE) was the most highly correlated with fruit maximum diameter (FMD) and fruit length (FLE) with r values of 0.937 and 0.801, respectively. Fruit length (FLE) was greatly correlated with fruit maximum diameter (FMD) and peduncle length (PLE) with r values of 0.741 and 0.616, respectively. Additionally, leaf blade width (LBW) was moderately correlated with leaf blade length (LBL) with r value of 0.612.

Results from the PCA based correlation matrix yielded principal components where the two first ones weighted 67.43% of the total variances with eigenvalues greater than 1 (Table 7).

Thus, the first principal component (PC1) obtained from the evaluation of different morphologic and agronomic valuable traits among *Solanum aethiopicum* gr. Gilo accessions expressed 45.90% of the total variance, and it was dependent on FWE, FMD, and FLE. Moreover, PC2

Table 7. Details on principal components analysis (greenhouse experiment).

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
LBW	0.15	0.64	0.26	-0.14	-0.02	0.65	0.20	-0.06
LBL	0.30	0.52	-0.24	-0.14	0.37	-0.57	0.27	0.16
TPH	0.22	0.10	-0.69	0.62	-0.13	0.26	0.00	0.01
FWE	0.50	-0.02	-0.02	-0.15	-0.03	-0.10	-0.32	-0.78
FLE	0.43	-0.23	0.01	-0.21	-0.65	-0.09	0.51	0.15
FMD	0.49	-0.01	0.12	-0.09	-0.02	0.08	-0.63	0.58
PLE	0.32	-0.50	-0.05	-0.10	0.64	0.34	0.32	0.04
LON	0.24	0.00	0.62	0.71	0.07	-0.20	0.14	-0.03
Eigenvalue	3.67	1.72	0.99	0.81	0.32	0.25	0.19	0.04
Percent	45.90	21.53	12.34	10.17	4.02	3.13	2.39	0.53
Cum %	45.90	67.43	79.77	89.94	93.95	97.09	99.47	100.00

PC: Principal component, LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number

contributed 21.53% of the total variability and was tied to LBW and LBL (Figure 6).

The phenotypic hierarchical cluster analysis was carried out to display the relationship structure among 57 accessions of *Solanum aethiopicum* gr. Gilo. Phenotypic similarity was calculated from 7 agro-morphological traits (quantitative traits) based on Ward aggregation distances. Due to the lack of fruits at maturity stage, 24 accessions were excluded from the hierarchical cluster analysis. Two major clusters were clearly identified. Thus, cluster A consisted of 18 accessions, and cluster B was slightly smaller, with only 15 accessions (Figure 7).

3.2. The open field experiment (II)

A summary of the descriptive statistics (means, standard deviations, and maximum and minimum values) for the open field experiment (2022) is shown in Table 8. Descriptive analyses made from quantitative traits data of plant and fruit displayed wide range of variations among all 55 accessions of *Solanum aethiopicum* gr. Gilo. For instance, the minimum leaf blade width was 10.0 cm (for accession GKE11) and the maximum was 18.0 cm (for accessions GKE7, GKE13 and MZE33), leaf blade length ranged from 17.5 cm (for accession GKE11) to 25.5 cm (for accession GKE20), and total plant height was scaled from 120.0 cm (for GKE5) to 160.0 cm (for MZE27).

Besides, we also noted extent changes from qualitative traits of fruit on studied accessions. As an illustration, fruit weight ranged from 16.7 g (for accession MZE43) to 91 g (for accession MZE49), fruit length ranged from 3.5 cm (for accession MZE43) to 9.1 cm (for accession GKE4), fruit maximum diameter ranged from 2.1 cm (for accession MZE34) to 8.8 cm (for accession GKE4), peduncle length ranged from 2.2 cm (for accessions MZE23 and MZE41) to 4.0 cm (for accession GKE3), and locule number ranged from 4 (for accessions MZE23 and MZE58) to 9 (for accessions GKE19 and MZE37).

The statistical correlation test between all 8 studied quantitative traits showed corresponding correlation coefficients in Table 9. It was found that both positive and negative correlations prevail among morphological and agricultural valuable traits. Correlation coefficient r values were all significant at $P < 0.05$. For instance, more positive significant correlation coefficients (values above 0.7) are listed as follow; fruit length (FLE) was the highly correlated with fruit maximum diameter (FMD) with r value of 0.853. Additionally, leaf blade width (LBW) was greatly correlated with leaf blade length (LBL) with r value of 0.710.

Results from PCA based correlation matrix yielded principal components where three first ones weighted 65.65% of the total variances with eigenvalues more than 1 (Table 10).

The results of principal components analysis are shown in Figure 8. The first two components are displayed.

The first principal component (PC1) was obtained from the evaluation of different morphologic and agronomic valuable traits among *Solanum aethiopicum* gr. Gilo accessions expressed 28.65% of the total variance and it was dependent on FMD and FLE. PC2 contributed 23.60% of the total variability and was tied to LBW and LBL. The third component (PC3) accounted for 13.40% of total variance and it is more related to PLE and TPH.

The phenotypic hierarchical cluster analysis was carried out to display the relationship structure among 55 accessions of *Solanum aethiopicum* gr. Gilo. Phenotypic similarity was calculated from 7 agro-morphological traits (quantitative traits) based on Ward aggregation distances (Figure 9).

Five accessions were excluded in the hierarchical clustering analysis due to the lack of fruits at maturity stage. Two major clusters were clearly identified. Thus, cluster A consisted of 26 accessions, while cluster B was slightly smaller, with only 24 accessions.

3.3. General remarks

The summary of descriptive statistics of both experiments of agro-morphological characterization of different accessions of *Solanum aethiopicum* gr. Gilo implies that there are significant differences between accessions. Lester and Daunay (2003) previously reported on this finding. These

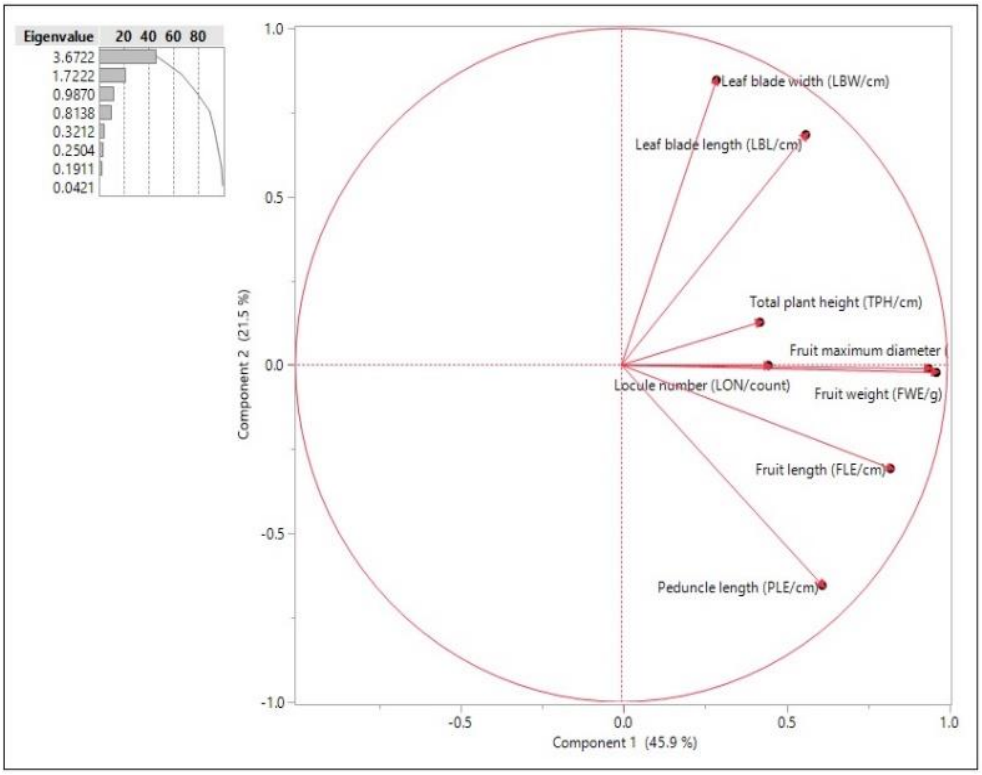

Figure 6. Summary plot on variables based Principal Components in the greenhouse experiment.

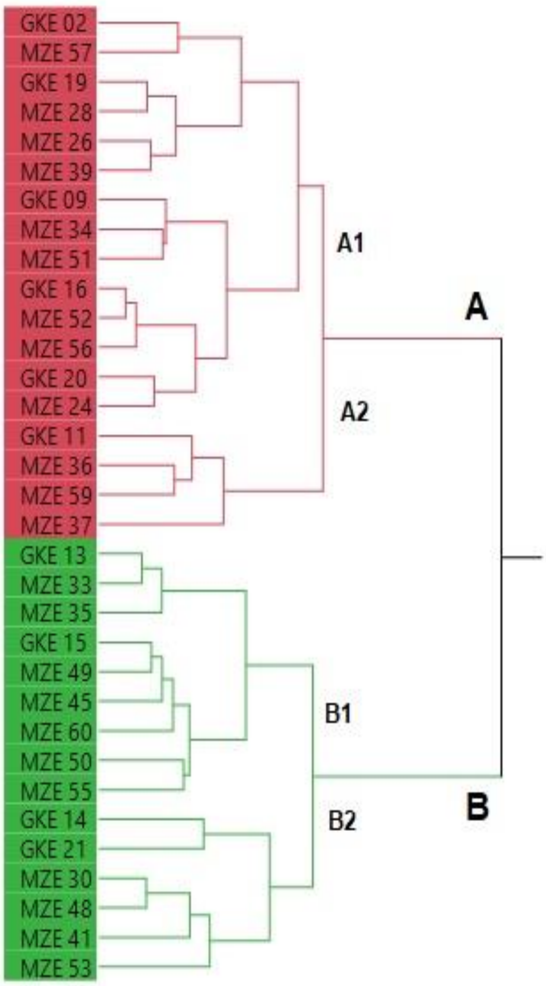

Figure 7. Hierarchical clustering analysis (HCA) dendrogram derived from greenhouse experiment.

Table 8. Descriptive statistic summary for the studied quantitative variables in the open field experiment.

Trait category	Descriptor abbreviations	Mean	STD	Range	
				Min	Max
Qualitative traits of plant	LBW	14.71	1.84	10.00	18.00
	LBL	21.45	2.14	17.50	25.50
	TPH	142.60	8.54	120.00	160.00
Quantitative traits of fruit	FWE	52.97	16.92	16.67	91.00
	FLE	5.38	0.94	3.54	9.15
	FMD	4.78	0.98	2.15	8.82
	PLE	2.97	0.42	2.17	4.00
	LON	6.16	1.18	4.00	9.00

LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number

Table 9. Correlation Coefficient between descriptors in the open field experiment.

Row	LBW	LBL	TPH	FWE	FLE	FMD	PLE	LON
LBW		0.710	0.155	-0.084	0.092	0.025	-0.164	-0.189
LBL			0.172	-0.178	0.032	-0.043	-0.105	-0.001
TPH				-0.023	0.215	0.177	0.032	0.008
FWE					0.282	0.341	-0.019	0.335
FLE						0.853	0.037	0.220
FMD							-0.115	0.355
PLE								0.011
LON								

LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number

Table 10. Details on principal components analysis (open field experiment).

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
LBW	-0.03	0.65	-0.11	0.15	-0.21	0.21	0.68	-0.05
LBL	-0.05	0.63	-0.08	0.37	-0.01	-0.13	-0.65	0.11
TPH	0.16	0.28	0.55	-0.19	0.72	0.21	0.03	0.00
FWE	0.39	-0.17	-0.28	0.29	0.03	0.80	-0.16	0.01
FLE	0.57	0.14	0.18	-0.21	-0.33	-0.11	-0.14	-0.66
FMD	0.60	0.08	0.01	-0.23	-0.18	-0.18	0.06	0.71
PLE	-0.03	-0.19	0.73	0.54	-0.35	0.06	0.06	0.13
LON	0.37	-0.14	-0.21	0.58	0.41	-0.46	0.25	-0.14
Eigenvalue	2.29	1.89	1.07	0.91	0.80	0.69	0.24	0.12
Percent	28.65	23.60	13.40	11.36	9.95	8.63	2.96	1.45
Cum %	28.65	52.25	65.65	77.01	86.95	95.58	98.55	100.00

PC: Principal component, LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number

researchers stated that the fruits and leaves of *Solanum aethiopicum* vary in shape and size within and between cultivar groups (Gilo, Kumba, Shum, and Acelatum).

When the mean values of different quantitative agro-morphological traits were compared, it was observed that there was a significant difference between experiments (or between greenhouse and open field cultivation) in terms of plant development and yield features (Figure 10).

The greenhouse experiment produced significantly larger leaves (LBW and LBL) than the open-field experiment. In contrast, yield characteristics (FWE, FLE, and FMD) were better in the open field experiment than in the greenhouse experiment. Although the obtained mean values of fruit weight in both experiments (25.75 and 52.97 g) were lower than the mean value reported by Prohens et al. (2005) on the morphological diversity assessment between three accessions of *Solanum aethiopicum* gr. Gilo and other eggplants, which was 74.30 g.

Substantial variations between experiments can be identified by analyzing other morphological traits, particularly qualitative traits (Table 11). Some of these variations include the distribution of anthocyanin in plants and leaves (ADP and ADL).

For instance, plants and leaves in greenhouse experiment had higher anthocyanin levels than plants and leaves in open field experiment. Similarly, in greenhouse experiment, the leaves had more prickles and were hairier than in open field experiment.

Furthermore, in the greenhouse experiment, eggplants had a higher fruit load (FLO) than in the open field experiment. However, the yield characteristics (quantitative traits) change in favor of the open field experiment at the maturity stage. The high seed content (SEC) observed in the open field experiment confirms the above. In summary, greenhouse-grown eggplants have better overall plant qualitative traits, but their fruit yield qualities are not substantial. The findings of multiple correlation analysis were used to compare the two

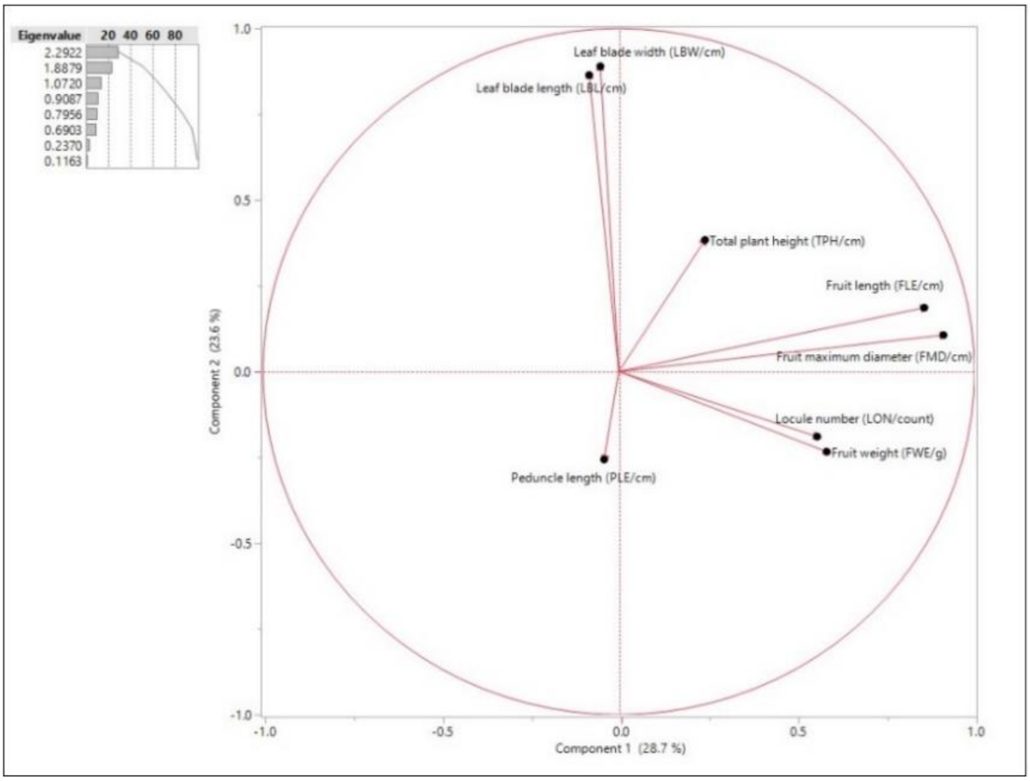

Figure 8. Summary plot on variables based Principal Components in the open field experiment.

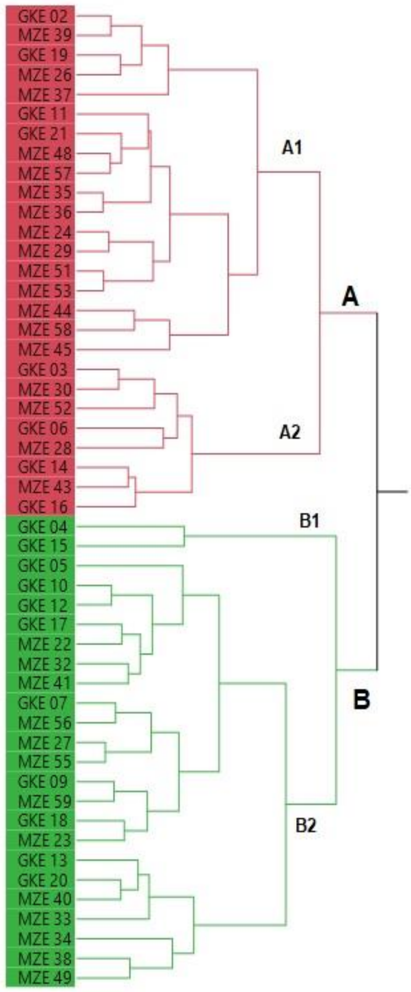

Figure 9. Hierarchical clustering analysis (HCA) dendrogram derived from open field experiment.

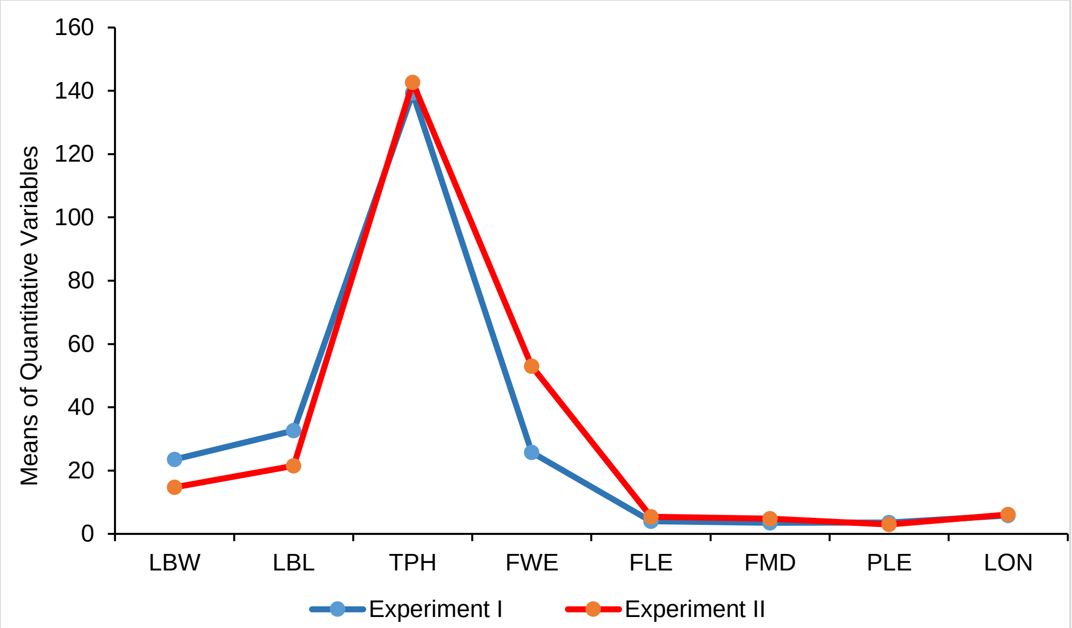

Figure 10. Means comparison of experiments I (greenhouse) and II (open field) (LBW: Leaf blade width, LBL: Leaf blade length, TPH: Total plant height, FWE: Fruit weight, FLE: Fruit length, FMD: Fruit maximum diameter, PLE: Peduncle length, LON: Locule number).

Table 11 Range and mean of qualitative traits between experiments.

	Experiment I		Experiment II	
Descriptors	Range (Min-Max)	Mean	Range (Min-Max)	Mean
GHA	1-7	4.33	3-7	3.32
LBO	3-9	6.15	5-7	6.36
ADP	1-7	5.06	1-5	3.16
ADL	1-7	5.00	1-5	3.08
LPR	0-5	1.03	0-0	0.0.
LHA	3-7	4.57	0-3	0.06
CCO	3-3	3.00	3-3	3.00
FLO	1-5	2.09	0-7	1.76
SCO	1-5	3.36	1-3	1.08
PCO	1-3	1.96	1-5	1.15
VTY	3-5	3.48	3-5	3.28
PFC	1-1	1.00	1-5	4.12
SFC	1-1	1.00	0-5	4.04
FCD	1-1	1.00	1-7	1.64
FUC	0-0	0.00	0-0	0.00
FGL	3-3	3.00	3-3	3.00
FCU	1-1	1.00	0-1	0.54
FAS	3-5	3.66	3-7	4.88
PMD	5-7	6.15	5-5	5.00
FCS	1-7	5.12	1-7	3.60
PGF	3-3	3.00	3-3	3.00
PHF	1-3	2.75	1-3	2.76
FEB	1-5	3.96	1-3	1.60
FSH	3-5	4.51	1-5	4.84
PCP	1-3	2.09	1-3	1.20
SEC	1-3	1.06	1-3	2.92
FCP	0-1	0.06	0-0	0.00
PGP	0-1	0.06	0-1	0.22
ACF	3-7	6.63	1-7	2.72

GHA: Growth habit, LBO: Leaf blade lobes, ADP: Anthocyanin distribution in plant, ADL: Anthocyanin distribution in leaves, LPR: Leaf prickliness, LHA: Leaf hairness, CCO: Corolla color, FLO: Fruit load, SCO: Stem color, PCO: Petal color, VTY: Varietal type, PFC: Predominant fruit color, SFC: Secondary fruit color, FCD: Fruit color distribution, FUC: Fruit undercalyx color, FGL: Fruit glossiness, FCU: Fruit curvature, FAS: Fruit apex shape, PMD: Position of the maximum diameter, FCS: Fruit cross-section, PGF: Presence of grooves on fruit, PHF: Presence of hole in fruit, FEB: Fruit end button size, FSH: Fruit shape, PCP: Presence of chlorophyll on the pistil scar, SEC: Seed content, FCP: Fruit calyx prickliness, PGP: Presence of a greenish ring next to the peel, ACF: Average color of the flesh experiments once more (Figure 11). It was discovered that highly correlated variables represented fruit quantitative traits. The greenhouse experiment had fruit weight (FWE) highly correlated to fruit maximum diameter (FMD) (r=0.937), as well as fruit weight (FWE) highly correlated to fruit length (FLE) (r=0.801), and the open field experiment had fruit length (FLE) highly correlated to fruit maximum diameter (FMD) (r=0.853). This means that the fruit descriptor variables were more dependent upon one another than the plant descriptor variables.

The two phenograms or hierarchical clustering analyses (HCA) generated using eight morphological descriptors based on the Ward aggregation distance clustering method clearly displayed the phonetic relationship among the accessions based on similarity and relatedness of eggplants. For the greenhouse experiment, it separated the 33 accessions (from 57 accessions originally assessed) into two major clusters (cluster A and cluster B) and it was found that each cluster accommodated accessions from both Gakenke and Musanze districts. A thorough examination of the phenotypic clustering results (greenhouse experiment) and morphological traits' mean performances (summary on descriptive statistics on quantitative traits-greenhouse experiment), have revealed that Cluster "B" does accommodate all superior elements in terms of fruit quantitative traits such as; fruit weight (FWE-MZE41), fruit length (FLE-MZE53), fruit maximum diameter (FMD-MZE41), peduncle length (PLE-MZE53 and MZE48) and locule number (LON, MZE53) as well as plant quantitative traits such as; leaf blade width (LBW-MZE53), leaf blade length (LBL-GKE14) and total plant height (TPH-GKE21). Besides, cluster "A" does also contain superior accessions in regard to LBW, LBLT and LPH (qualitative traits of the plant). These results made accessions from this cluster promising donor parents for multiple traits.

For the open field experiment, it separated the 50 accessions (from 55 accessions originally assessed) into two major clusters (cluster A and cluster B) and it was found that each cluster accommodated accessions from both Gakenke and Musanze districts. A thorough examination on the phenotypic clustering results (open field experiment) and morphological traits' mean performances (summary on descriptive statistics on quantitative traits-open field experiment), have revealed that Cluster "B" does accommodate all superior elements in terms of fruit quantitative traits such as; fruit weight (FWE-MZE49), fruit length (FLE-GKE4), fruit maximum diameter (FMD-GKE4), as well as plant quantitative traits such as; leaf blade width (LBW-GKE7, GKE13, and MZE33), leaf blade length (LBL-GKE20) and total plant height (TPH-MZE27). Although, cluster "A" does also contain superior accessions in regard to fruit qualitative traits of the plant like peduncle length (PLE, GKE3) and locule number (LON-GKE19 and MZE37). These results made accessions from mainly cluster B promising donor parents for multiple traits.

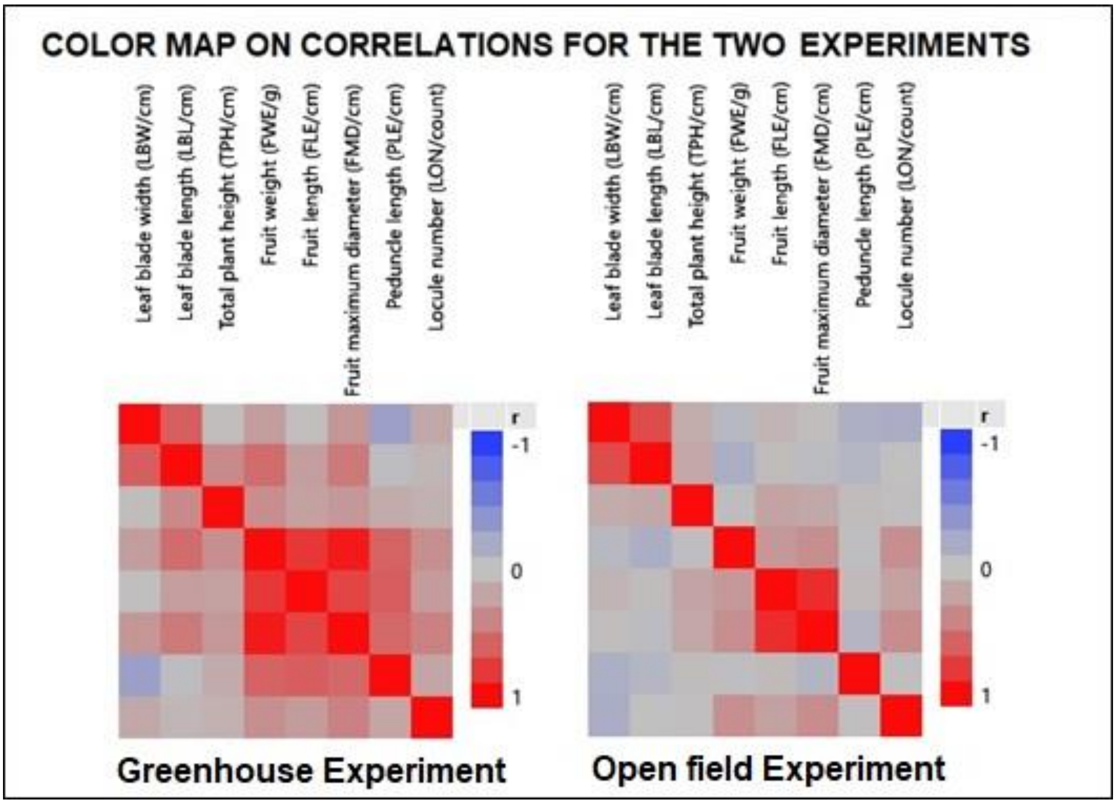

Figure 11. Comparison of multiple correlation analysis.

Furthermore, the evidence based on the PCA correlation matrix in greenhouse experiment has assured the significance of fruit quantitative variables (FWE, FMD, and FLE) in the first principal component (PC1), which explained 45.90% of the total variance within the studied germplasm. Similarly, in open field experiment, fruit quantitative variables (FMD and FLE) were substantial in the first principal component (PC1), which explained 45.90% of the total variance within the studied germplasm.

This means that the overall differences observed in *Solanum aethiopicum* gr. Gilo germplasm both in greenhouse and in open field experiments were due mainly to fruit quantitative traits. In other words, the chosen morphological descriptors, particularly those related to yield and fruit quality, were conclusive for eggplant germplasm characterization. The phenotypic results provide new awareness on the agronomic behavior of several accessions. For future breeding programs, accessions with high average fruit weight, fruit maximum diameter, and fruit length could be taken into consideration.

In brief, this high diversity is often based on high discriminatory fruit traits of *Solanum aethiopicum* and has been highlighted in diversity studies by Adeniji et al. (2012), Plazas et al. (2014), Sakhanokho et al. (2014), and Bationo-Kando et al. (2015). It was also reported that different fruit sizes and shapes exist among individuals of *Solanum aethiopicum* gr. Gilo (Taher et al., 2017). Our results show the existence of an extensive phenotypic diversity in *Solanum aethiopicum* gr. Gilo which is in agreement with similar results by Kouassi et al. (2014). Observations from fruit traits reaffirm that the used germplasm of *Solanum aethiopicum* belongs to the Gilo group and it is more particularly similar to one of three sub-groups reported by the same authors in Côte d'Ivoire and which is known as “N'Drowa”. Thus, it was found that the N'Drowa subgroup has larger leaves and larger fruits. Several scholars pointed out the high morphological diversity of scarlet eggplant on the African continent, as well as the existence of large germplasm collections made of several landraces in countries such as Burkina Faso, Cameroon, Côte d'Ivoire, Ethiopia, Gabon, Ghana, Kenya, Nigeria, Senegal, Tanzania, Uganda, Zambia, Zimbabwe, and also Rwanda. Furthermore, those listed countries are seen as domestication centers of *Solanum aethiopicum* (Sseremba, 2019).

4. Conclusion

Landraces are crucial in contemporary plant breeding programs due to their extensive genetic diversity compared to modern varieties. As a direct consequence, they may be useful to expand the genetic base of modern cultivars. In this study, the genetic and phenotypic diversity of the largest germplasm collection of *Solanum aethiopicum* gr. Gilo accessions from Rwanda was assessed using the most recent molecular markers, the iPBS retrotransposon markers system for genetic diversity, and a couple of descriptors for eggplant morphological characterization.

Similarly, phenotypic diversity analysis revealed a high level of diversity among *Solanum aethiopicum* gr. Gilo accessions. Multiple correlations disclosed that plant and fruit-related descriptors diverge enough to distinguish between germplasm populations. Fruit variables/descriptors, for instance, were more interdependent than plant variables/descriptors. Furthermore, phenotypic (hierarchical) clustering shows that clusters were formed primarily on the basis of fruit quantitative traits rather than plant quantitative traits. This means that fruit quantitative traits are critical for phenotypic characterization of *Solanum aethiopicum* gr. Gilo eggplant.

The information produced by deep characterization of base collection could be useful in future germplasm characterization. Thus, the conservation of heritage of *Solanum aethiopicum* gr. Gilo may be provided for future generations.

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