



STABILITY OF TOMATO (*SOLANUM LYCOPERSICUM* [L.]) FRUIT WEIGHT AND DIRECT AND INDIRECT CONTRIBUTION OF AGRONOMIC TRAITS UNDER POLYHOUSE CONDITION IN SUDAN AGRO-ECOLOGY

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ABSTRACT

The study was carried out to understand phenotypic variability and stability concerning fruit weight and quality, as well as the contribution of various traits to fruit weight per plot under polyhouse conditions in Sudan agroecology during the 2019-20 growing season. Six tomato cultivars were cultivated in a randomized block design (RBD) with four replicates in a polyhouse. Data collected include phenological, morpho-physiological, fruit weight per plot, and quality traits. The findings indicated significant variability in both fruit weight and quality traits. Notably, the days to appearance of first fruit and mature fruit, as well as fruit height and width, total soluble solids (TSS), and fruit weight per plot were affected by the interaction between hybrid and microclimatic factors. The varieties 'TSU02', 'TSU03' and 'TSU05' demonstrated phenotypic insensitivity to these microclimatic factors, exhibiting moderately high fruit weight per plot. Furthermore, 'TSU04', 'TSU02' and 'TSU03' displayed stable performance for TSS across the years. The contribution of fruit weight and number of fruits per plant were significant in determining overall fruit yield, while individual fruit weight served as a valuable index for fruit yield improvement. The relationship between fruit weight per plot and indirect effects of fruit length and fruit per infructescence indicates a compromise in developing high-yielding varieties. Thus 'TSU02' and 'TSU03' emerged as a promising hybrid for enhancing fruit weight and total soluble solids in polyhouse cultivation within Sudan agroecology.

Keywords: Polyhouse, Tomato, Fruit, Weight, Cultivar, Yield.

INTRODUCTION

Tomatoes (*Solanum lycopersicon* [L.]) are a highly nutritious fruit vegetable in sub-Saharan Africa (USDA (2019). In 2020, global production reached approximately 186.821 million metric tonnes (MMT) from 5,051,983 hectares (FAOSTAT, 2020). Nigeria contributed 3,693.720 MT of fresh fruits from 844, 445 hectares, achieving an average fruit yield of 4.4 MT per hectare. In contrast, Egypt reported significantly higher production, with an average of 39.4 MT/ha (FAOSTAT, 2020). West Africa stands as the largest producer of fresh tomato fruits compared to East Africa (FAOSTAT, 2020). However, the region continues to import a substantial amount of processed tomato products and seeds, including both hybrids and open pollinated varieties (Sahel, 2017). The growing conditions for tomatoes in the rain-fed regions of Sudan agro-ecology are marked by heavy precipitation, delayed onset of precipitation, seasonal drought, high evapotranspiration, elevated temperature, and occasional thunderstorms (Nemeskéri, *et al.*, 2009, along with specific-soil related factors. In the open- field production, tomato fruits are often subjected to high levels of insect infestations (Nguyen and Ranamukhaarachchi, 2010) and diseases caused fungi and bacteria, leading to excessive and sometimes inappropriate pesticide use. In contrast, polyhouse cultivation is advantageous as it conserves water and land resources (Jensen, 2002), while allowing for year-round cultivation. This method can yield multiple harvests, particularly when utilizing early-maturing cultivars. Within the context polyhouse-grown tomatoes in Sudan's agro-ecology, critical micro-climatic factors include solar radiation, water stress (Gautam *et al.*, 2013), and high temperatures, which can range from 38°C and 43°C. The heat stress can significantly impact physiology, influencing growth, flower production (Boulard *et al.*, 2011), fruit set, and fruit development, and overall fruit yield (Sharma, *et al.*, 2019; Lekshmi and Celine, 2015; Singh *et al.*, 2019; Sotelo-Cardona *et al.*, 2021). In protected cultivation, it is possible to control the



micro-climate conditions surrounding the plants (Sharma, *et al.*, 2019; Cheema *et al.*, 2013), thereby enhancing fruit weight and productivity. However, in sub-Saharan Africa, the commonly grown fresh market tomato varieties are not well adapted for cultivation in polyhouse. Consequently, tomato growers in Sudan's agroecology are actively seeking improved varieties that can consistently deliver high fruit yield and quality standards suitable for protected cultivation. The morphology, physiological attributes, yield characteristics, and stability of tomato fruits in the polyhouse are influenced by the genotypic response to various microclimatic and macroclimatic factors, as well as biotic and abiotic stresses. The interaction between genotype and environment (GEI) complicates the prediction of genetic progress under selection.

In Sudan's agroecology, sustainable production is hindered by adverse weather conditions. Given, the varying microclimatic factors in polyhouse across different years and locations, a pronounced GEI effect on fruit yield is anticipated. As a result, a genotype that performs well in one environment may not yield the same results in another, complicating the selection process. To estimate the stability of agronomic traits across different years and locations, techniques such as the Finlay and Wilkison regression technique, and Shukla's (1972) stability variance (σ^2), Wricke Ecovalence's (1962) and Francis and Kannenburg (1978) are commonly employed. Additionally, fruit weight is determined by additive and non-additive gene action (Vyas *et al.*, 2018; Tasisa *et al.*, 2018), and is interconnected with various vegetative, reproductive, fruit yield and fruit yield-related traits (Cheema, *et al.*, 2013). While the correlation analysis assesses the association between traits, it is not necessary for evaluating the effects of independent factors on dependent variable such as yield. The path analysis assesses the contribution of independent variables, both direct and indirect effects on the dependent variable, which in this case is fruit weight (Kingslover and Schemske, 1991). This procedure is essential when the goal is to enhance fruit weight through the selection and simultaneous improvement of related traits. Tomato fruit production for the fresh market raises significant concerns regarding sustainability, particularly in the context of household nutrition and climate impact.

Further, the literature lacks comprehensive information on the variability inherent in tomato varieties, the association between physiological and agronomic traits, and their contributions fruit yield under protected farming. While the practice of cultivating tomato in tunnels shows promise, factors such as elevated temperatures, varying humidity levels, and airflow limitations under polyethylene covers hinder the potential of protected cultivation in the Sudan regions. Tomato growers often face challenges assessing productive varieties. To improve productivity through polyhouse cultivation, it is crucial to consider the diversity of microclimate attributes across geographic areas and cropping systems. This research aims to 1) quantify morpho-physiological variation among tomato cultivars under polyhouse condition, 2) evaluate the interaction between the cultivar \times environment (both micro and macro) concerning fruit weight and quality, and 3) identify the contributions of morpho-physiological and fruit weight component traits to the overall fruit yield.

MATERIALS AND METHODS

Germplasm and Location

The seeds of beefsteak indeterminate tomato hybrid varieties ('TSU01', 'TSU02', 'TSU03', 'TSU04', 'TSU05' and 'TSU06') were received from Agro dealers in Jalingo, Taraba state, Nigeria. These varieties were evaluated during the off seasons from January to April in 2019-20, a period characterized by high temperatures (35°C to 39°C), low humidity, and significant heat waves. The polyhouse had dimensions of 102.72 meters \times 57 meters, with a useable area of 99.37 \times 54.72 meters for this research. Facilities in the polyhouse included drip and sprinkler irrigation systems, as well as exhaust fans, and horizontal airflow. The rainy season in Jalingo typically spans from May to October, with an average temperature of 29°C and maximum temperatures ranging from 31°C and 39°C during the January and April timeframe.

Nursery Management and Crop Husbandry

Humus soil and perlite received from agro-dealers were blended in a 3:1 ratio. The mixture was filled into 54 multi-pot seedling trays, with each genotype assigned six trays. Water was applied to trays immediately after sowing. Two weeks post-emergence, a foliar application of 125 Kg of N P K



(18:18:18) was dissolved in 500 litres of water was conducted using hand-held sprayer. Four weeks after sowing, 30 mL of fungicide VIVA® S.L (with Oxamyl 240 as the active ingredient; produced by Almandine Corporations S.A, Switzerland) was diluted with 20 liters of water. The seedlings were immersed for 5 minutes to disinfect them prior to transplanting into the polyhouse. The soil utilized was sandy loam with a pH of 5.67. A completely randomised design with four replicated treatments was used. The experimental field was ploughed, harrowed, and structured into double row flat ridges spaced 0.5 meters apart, with 1.1 meter alley separating the rows. Four weeks later, tomato seedlings were hand- transplanted into the ridges, with in-row and between row spacing of 0.5 × 0.6 meters. Each two-row plot accommodated 140 plants.

Two weeks after transplanting, 25 kg of a compound fertilizer (N18: P18: K18) was dissolved in 100 liters of water. Ten (10) millilitres (mL) of this fertilizer solution were applied to each plant using a drip irrigation system. Subsequently, a second fertilizer formulation (N 17: P9: K27) was also mixed with 100 liters of water and applied at the same rate of 10 mL per plant via drip irrigation system. Weeds were managed through rouging and hoeing. To control insect attacks and diseases transmitted by insects were managed by spraying 50 mL of Abamectin®, 40 mL of Imidacloprid® (EC) from Hebei Xintian Biological Technology Co., Ltd., and 100 g Mancozed® (WP) from Sigma-Aldrich Chemie were combined in 30 liters of water and applied at three and eight weeks post-transplanting. Each dripping point was set to deliver 0.59 L of water to each plant daily.

Measurement of Agronomic and Fruit Quality Traits

The study measured several key horticultural traits; the number of days from sowing in the nursery to the appearance of the first flower, as well as the days required for 50% of the plants to produce flowers. The timing for the appearance of the first fruit and first mature fruit was also recorded, starting from the date of sowing in the nursery. The duration from first fruit to its maturity was calculated as the number of days taken from this transition. Vine length (m) at 50 % flower appearance was measured from the base of each plant to the apex of the main stem using a meter rule. Upon culling, the total number of harvested fruits per plot was counted, and their weight was recorded using a sensitive weighing balance (Kilogram). To assess fruit dimensions, ten randomly selected fruits were measured for height (centimeter) from the tip to the blossom end using a hand-held electronic Vernier caliper, while the fruit width (centimeter) was determined on the fruit at harvest using the same type of caliper. The harvested tomato fruits were sorted into marketable and non-marketable groups. Before analysing fruit quality, mature tomato fruits were collected from each plot at the time of culling and blended in the laboratory. The total soluble solids and acidity were determined using a handheld refractometer (model ATC-1, Atago, Bellevue, WA) and a pH meter, respectively. The average trait values were estimated using Ms Excel software. The error variance was tested for homogeneity.

Data Analysis

The PROC GLM procedure of Statistical Analysis System (SAS) (ver. 9.4, SAS Institute, CARY, NC) was used to decompose the total variability into sources related to genotypes (G), Environment (E), and interactions between genotype × environments (GEI). In this analysis, the microenvironment was treated as a random factor, whereas the cultivar was considered a fixed factor. If the interaction was not statistically significant, the multiple comparisons of the main effect were conducted using Tukey Honesty Studentized test at 5 % and 1 % of probability levels. Following the detection of GEI, the stability of performance was evaluated. Six parametric stability methods including Wricke ecovalence, Shukla stability variance, Coefficient of variance (CVi), and Genotype by Environment (GE) variance component and Kang rank sum (KR) were utilized to explain GEI. The association between traits were examined using the PROC CORR procedure in SAS (ver.9.4, SAS Institute, Cary, NC). Further, the direct and indirect contribution of independent factors (traits) to dependent variable (fruit weight per plot) was calculated using the PROC PATH in SAS (ver.9.4, SAS Institute, Cary, NC). In this context, fruit weight per plot was the response variable, while other traits functioned as causal variables.



RESULTS AND DISCUSSION

Genotypic Variation and Genotypic Mean Performance

In Sudan agro ecological zones, tomato growers utilizing polyhouse tend to favour in early or medium-maturing varieties that exhibit high fruit weight and minimal sensitivity to microclimatic factors. Findings revealed statistically significant mean squares ($P \leq 0.01$) for several traits, including the duration (days) to first flower appearance, vine length at flowering, number of fruits per infructescence, individual fruit weight, total fruit number per plot, fruit/infructescence, and fruit acidity (Table 1). This aligns with the genetic characteristics and varying responses of different tomato varieties to microclimatic conditions. Significant interactions ($P \leq 0.01$) were observed for years and genotype-environment interaction (GEI) the duration of fruit maturity, fruit brix and fruit weight. This suggests that the microclimate conditions within the polyhouse have varied inconsistently over the years and are insufficient for accurately defining phenotypic variability, highlighting the need for multi-location testing (Ummiyah *et al.*, 2021). The non-cross over performance related to days to first flowering, individual fruit weight per plot, total fruit per plot, fruit count per infructescence, and fruit pH provides clear evidence of a linear response of the tomato genotypes to micro-environmental factors, along with high predictive accuracy for these traits.

Additionally, while the tomato varieties display genetic heterogeneity, the environment within the polyhouse remain homogeneous. Significant genotype by environment (GEI) mean squares for total soluble solids is similar to the findings of Panchbhैया *et al.*, (2018) and Akinyode, (2021) regarding tomato fruits cultivated in open fields. The variation in fruit quality, particularly in terms of fruit brix levels, observed over the years may be attributed factors such as elevated temperature, heat and light intensity. Bhandari *et al.*, (2022) noted a considerable impact of high temperatures and light duration on total soluble solids (TSS) in tomato fruits. Nonetheless, the temperature fluctuations in a polyhouse are often greater due to limited airflow; cooling is typically achieved through sprinkler irrigation and ventilation. Various tomato varieties exhibited a wide array of variations in morphological traits, phenological aspects, and fruit weight, suggesting differing responses to both micro-and micro-environmental factors within the polyhouse. Consequently, a stability is essential to identify varieties that consistently produce desirable traits, such as days to maturity, fruit weight, and total soluble solids. The vine length was longest in 'TSU03' genotype at 94 cm, followed closely by 'TSU05' with 89 cm. 'TSU06' had earliest flowering time, while TSU05 flowered later (Table 2). The individual fruit weight per plot as recorded in 'TSU01' at 141.79 g. The hybrid 'TSU04' excelled in fruit width, whereas open pollinated hybrid variety 'TSU06' produced an impressive eight fruits per infructescence.



Table 1: Phenological, Fruit Quality and Yield Traits among Tomato Varieties across 2019-20.

Source of variation	df	Days to flower appearance (d)	Vine length (cm)	Fruit yield (g)	Fruit/plot	Fruit/infructescence	Fruit pH
Cultivar	5	48.90**	613.65**	353.31**	496431.88**	7.14**	0.27**
Year	1	1.22	18.15	133.33	60062.50	0.03	0.05
Cultivar × Year	5	7.78	76.40	155.18	221164.93	0.08	0.06
Error	36	5.27	38.08	77.63	113708.08	0.05	0.05
CV (%)		3.9	7.7	6.5	11.2	4.1	4.7
Mean		62	79.87	135.75	3004.63	5.42	4.85

** Significant at 0.05, 0.01%, level of probability.



Fruit acidity ranged from 4.65 in 'TSU04' to 5.18 in 'TSU06', and while 'TSU06' yielded the highest number of harvested fruits per plot, the individual fruit size was relatively small.

Table 2: Mean Values of Cultivars for Phenological, Fruit Yield and Quality in Tomato Varieties across 2019-20.

Genotype	Days to first flower appearance (d)	Vine length at 50% flowering (cm)	Fruit width (cm)	Number of fruits/infructescence	Fruit pH	Number of fruits/plot
TSU 01	61ab	80.09cd	4.80b	6b	4.74b	3074.10ab
TSU 02	59b	84.29bc	5.06a	6b	4.94ab	2996.31ab
TSU 04	65a	81.09ab	5.24a	6b	4.64b	2703.09b
TSU 03	63a	93.99a	5.22a	6b	5.18a	2765.01b
TSU 06	58b	50.01d	3.84b	9a	4.84b	3480.81a
TSU 06	62a	88.95b	3.72b	6b	4.86ab	3011.01ab

Values in columns followed by the same letter are not significantly different, $P < 0.05$.

Stability of Maturity Time, Total Soluble Solid and Fruit Weight

The number of days required for fruit maturation is crucial for achieving three production cycles annually, as well as planning harvesting and fruit shipment. This duration ranges from 96 days for 'TSU02' to 100 days for 'TSU03'. Two varieties, 'TSU06' and 'TSU04' exhibited identical maturation periods of 97 days. 'TSU01' and 'TSU05' (Table 3) with smaller deviation from the mean across years for days to fruit maturity and had the lowest Shukla stability variance, making them ideal for stable performance for time to fruit maturity (Table 4).

Table 3: Mean separation for Fruit Maturity, Total Soluble Solids and Fruit Weight in Tomato Varieties during 2019-20 in Sudan agroecology.

	Year	Days to fruit maturity	Total soluble solids	Fruit weight (kg)
TSU01	1	31a	4.97d	381.50e
	2	31a	3.50e	527.80a
TSU02	1	29c	5.25a	389.16d
	2	29c	5.25a	391.06c
TSU04	1	25e	3.65e	382.75e
	2	25e	3.66e	382.75e
TSU06	1	28d	5.25a	464.10b
	2	28d	5.25a	462.22b
TSU03	1	29a	5.05c	426.94c
	2	30b	5.20b	379.79f
TSU05	1	26e	3.50g	366.36g
	2	32a	5.25a	362.50g

Values in columns followed by the same letter are not significantly different, $P < 0.05$

	df	Mean squares	
Cultivar (C)	5	30.14**	7105.08**
Year (Y)	1	22.58**	2788.9**
C × Y	5	13.00**	3215.18**
Error	36	1.68	363.79
CV (%)		4.6	4.3
Mean		28	446.37

*, ** Significant at 0.05, 0.01%, level of probability.

Table 4: Stability values for Phenological, Fruit Yield and Fruit Quality Traits in Tomato Varieties during 2018-19 in Sudan agroecology

Cultivars	Stability models	Days to mature fruit	Total soluble solids	Fruit yield
TSU01	Wricke's ecovalence	0.38	1.21	8466.68
	Shukla stability variance	0.12	1.68	12160.52
	Regressions	1.53	-17.70	9.04
	Coefficient of variation	1.78	24.61	22.75
	GE	2.16	0.36	158.72
	Kang Rank Sum	3.99	10	4
	Mean	99.25	4.23	454.65
TSU02	Wricke's ecovalence	1.32	0.003	102.75
	Shukla stability variance	1.52	-0.14	-385.62
	Regressions	0.00	0.00	0.11
	Coefficient of variation	0.00	0.00	0.33
	GE	1.88	0.71	2667.95
	Kang Rank Sum	11	4	2
	Mean	96	5.25	390.18
TSU04	Wricke's ecovalence	1.32	0.003	372.17
	Shukla stability variance	1.53	-0.13	18.51
	Regressions	0.00	0.00	-0.68
	Coefficient of variation	0.00	0.00	2.03
	GE	1.88	0.71	264.99
	Kang Rank Sum	5	0	1
	Mean	97	5.25	386.3
TSU06	Wricke's ecovalence	1.32	1.61	162.90
	Shukla stability variance	1.52	2.27	-295.01
	Regressions	0.00	22.50	8.11
	Coefficient of variation	0.01	29.87	0.28
	GE	4.88	0.23	2649.30
	Kang Rank Sum	4	10	3
	Mean	97.25	4.44	463.16
TSU03	Wricke's ecovalence	4.13	0.008	1591.91
	Shukla stability variance	5.74	-0.13	392.01
	Regressions	2.77	-0.60	0.13
	Coefficient of variation	3.19	0.97	0.42
	GE	1.04	0.71	2669.23
	Kang Rank Sum	7	10	4
	Mean	99.75	3.63	399.91
TSU05	Wricke's ecovalence	0.63	0.02	98.48
	Shukla stability variance	0.49	-0.14	-392.00
	Regressions	1.69	1.89	0.13
	Coefficient of variation	1.98	2.66	0.42
	GE	2.09	0.71	2669.33
	Kang Rank Sum	5	4	1
	Mean	98.88	5.13	361.43

The Finlay and Wilkinson regression coefficient values greater than one ($b_i > 1$) were observed in 'TSU01', 'TSU05' and 'TSU03' indicating a heightened sensitivity of these varieties to micro environmental changes within the polyhouse, as well as a greater specificity of adaptability to late fruit maturation. In contrast, three varieties 'TSU 02' 'TSU04' and 'TSU06' exhibited regression coefficients less than 1.00, indicating insensitivity to microclimatic factors within the polyhouse and demonstrating stable performance regarding days to maturity. The coefficient of variance was notably low (0.00) in cultivars 'TSU02', 'TSU04' and TSU 06. The GE variance components ranged from low (1.04 in 'TSU03') to high (2.16 in 'TSU01'). Three varieties 'TSU06', 'TSU01' and 'TSU05' with high GE



variance, were regarded as stable concerning days to mature fruits. Further, 'TSU06' and 'TSU04' displayed equal values for the coefficient of variance with 97 days, while 'TSU02' had 96 days to fruit maturation making them the most desirable options. The stability parameters indicated that cultivars 'TSU02' 'TSU04' and 'TSU06' are promising candidates for consistent maturation times. The varieties 'TSU06' and 'TSU02' exhibited the lowest Kang rank sum, with 99 days and 97 days to mature fruit deemed the most desirable.

The total soluble solids (TSS) which serves as an index for sweetness, significantly influences product flavour and consistency. Noteworthy, genotypes ($P \leq 0.01$) and genotype by environment interaction mean square were identified for TSS. The varieties 'TSU02' and 'TSU 06' achieved the best performance for TSS in 2019 and 2020 (Table 3). Both varieties, 'TSU04' and 'TSU02', had equal (0.03) magnitude and the lowest value for Wricke ecovalence, showing minimal response and smaller deviations from the mean for TSS across different environments (Table 4). These varieties are more stable regarding TSS performance across years compared to others. The Shukla stability variance (σ^2_i) was positive and high for 'TSU01' and 'TSU06' indicating a more significant influence from microclimate factors, which illustrates their unsuitability. Conversely, 'TSU04' and 'TSU 02', and 'TSU05' demonstrated insensitivity to microclimatic variations, maintaining stable performance over years. The Finlay and Wilkinson regression coefficients exceeded unity for 'TSU01' and 'TSU06', while below unity for 'TSU02', 'TSU04' and 'TSU05'. This indicates suggests that 'TSU05', 'TSU04' and 'TSU02' displayed consistent performance across years despite microclimatic influences. Based on σ^2_i and W_i^2 , 'TSU 04', 'TSU02' and 'TSU03' showed stable TSS performance, year after year. In contrast, the Kang rank sum identified 'TSU02' and 'TSU04' as most desirable for total soluble solids (TSS) due to their lower values. A coefficient of variation index (CV_i) and high mean values for total soluble solids (TSS) in 'TSU02' indicates stability and desirability for fruit brix. Notably, tomato varieties that exhibited superior for fruit brix in 2019 in one environment maintained their advantageous traits across different environments in 2020.

'TSU01' and 'TSU06' consistently demonstrated high fruit weight over years (Table 3), with b values exceeding unity (Table 4). None of the tomato varieties significantly outperformed 'TSU06', the leading variety in terms of fruit weight per plot when averaged across years. However, 'TSU02' achieved a high fruit weight per plot during the 2020 evaluation, while 'TSU06' excelled in the 2019 evaluation (Table 3). This underscores the importance of developing stable cultivars or enhancing microclimatic conditions to increase fruit weight per plot. According to the CV_i model, 'TSU06' characterized by a low CV_i and high fruit weight per plot, displayed minimal influence from microclimatic factors in the polyhouse and deemed stable for fruit weight. Wricke's ecovalence values were notably low for 'TSU 05' and 'TSU02' while 'TSU01' exhibited high values. The Shukla stability variance (σ^2_i) showed mixed results, with 'TSU04' recording the lowest stability variance at 18.51 and 'TSU03' having the highest. The ranking according to Kang's method ranged from 4 to 9, with 'TSU06' receiving the lowest rank, followed closely by 'TSU02', 'TSU05', 'TSU03', 'TSU01' and 'TSU04'. This stability assessment identified 'TSU01', 'TSU03' and 'TSU06' as stable varieties for fruit weight per plot. The GE variance component indicated that 'TSU03', 'TSU05', 'TSU06', and 'TSU02' showed less variation in fruit weight per plot across years, with high GE variance were stable. 'TSU05' and 'TSU02' had a smaller variation for fruit weight per plot across years, making them more stable in comparison to 'TSU01'. The low GE variance and high mean fruit weight per plot for 'TSU01' are deemed undesirable in polyhouse cultivation. According to the Finlay and Wilkinson regression coefficients, values less than one highlight greater adaptation to microclimatic factors. Two cultivars i.e. 'TSU01' and 'TSU06' with b values exceeding 1.0, exhibited heightened sensitivity to changes in the microenvironment over the years, indicating adaptability to high fruit-yielding environments. In contrast, four varieties viz. 'TSU02', 'TSU04', 'TSU 06', and 'TSU05' with regression coefficients below one were less responsive to changes in the in microenvironment, thereby enhancing their adaptation to specific low-fruit – yielding conditions. The model identified 'TSU02', 'TSU03' and 'TSU05' as stable hybrid for fruit weight per plot. In contrast, 'TSU01' which exhibits moderately high fruit weight per plot, is unstable. This suggests that developing tomato varieties with optimal performance across diverse ecological conditions will pose challenges. Consequently, to achieve high fruit weight in polyhouse settings, the



focus should be on high fruit-yielding varieties that demonstrate a significant degree of general adaptability.

Contribution of morpho-physiological and agronomic traits to fruit weight revealed that the indirect effects of these traits were generally less significant than their direct effects. Notably, fruit weight exhibited the most substantial positive direct contribution to fruit weight per plot, with its highest indirect influence stemming from a decrease in the number of fruits per infructescence, fruit brix, fruit infructescence/plant and fruit length (Table 5). This indicates that certain traits are negatively associated with fruit weight. Improvements in phenotypic characteristics such as number of fruits per infructescence, total soluble solids, fruit infructescence per tomato plant and fruit length will not lead to an increase in fruit weight. Conversely, both the weight of each fruit and number of fruits recorded on each plant demonstrated a strong positive and direct influence on overall fruit weight. In a separate study conducted by Sharma *et al.*, (2019), a significant correlation was observed among fruit weight, individual fruit weight and the number of fruits per plant in various tomato varieties cultivated under a protected environment. This suggests that genetic enhancement targeting individual fruit weight and fruit yield per plant will contribute to increased fruit weight.



Table 5: Path Analysis depicting contribution of Agronomic and Fruit Quality Traits on Fruit Yield of Tomato Varieties in polyhouse in Sudan agroecology.

	Individual fruit yield	Fruit diameter	Days to flowering	Vine length at flowering	Sepal length	Sepal width	Petal length	Days to fruit appearance	Fruit length	Fruit width	Fruits /plant	Fruits /infructescence	Fruit infructescence /plant	Fruit brix
Direct on fruit yield	0.475	-0.493	-0.191	-0.651	0.350	-0.040	-0.061	0.164	-0.286	-0.047	0.208	-0.269	-0.240	-0.054
Indirect via fruit width	-	-0.277	-0.035	-0.347	0.119	0.004	-0.020	-0.022	0.092	-0.010	-0.022	0.119	0.077	0.020
Indirect via fruit diameter	0.266	-	-0.072	-0.523	0.244	0.015	-0.016	-0.030	0.169	-0.031	-0.145	0.231	0.092	-0.005
Indirect via days to flower	0.086	-0.188	-	-0.264	0.192	0.010	0.008	0.074	0.063	-0.014	-0.097	0.126	0.048	-0.004
Indirect via vine length at flowering	0.253	-0.397	-0.077	-	0.235	0.020	-0.025	-0.007	0.174	-0.028	-0.133	0.232	0.009	-0.010
Indirect via sepal length	0.161	-0.345	-0.104	-0.437	-	0.016	-0.014	0.018	0.105	-0.029	-0.116	0.219	0.073	-0.007
Indirect via sepal width	-0.052	0.192	0.046	0.332	-0.142	-	-0.001	0.029	-0.076	0.020	0.098	-0.161	0.032	0.026
Indirect via petal length	0.153	-0.129	0.025	-0.264	0.082	0.000	-	-0.002	0.081	-0.002	0.035	0.064	-0.064	0.005
Indirect via days to fruit appearance	-0.065	0.091	-0.086	0.026	0.037	-0.007	0.001	-	-0.029	0.011	0.007	-0.048	-0.056	0.001
Indirect via fruit length	-0.154	0.292	0.042	0.396	-0.128	-0.010	0.017	0.017	-	0.006	0.079	-0.148	-0.033	0.011
Indirect via fruit diameter	0.102	-0.318	-0.056	-0.381	0.215	0.017	-0.002	-0.039	0.034	-	-0.138	0.184	0.049	-0.011
Indirect via fruit/plant	-0.051	0.344	0.089	0.415	-0.195	-0.019	-0.010	0.006	-0.108	0.031	-	-0.198	-0.080	0.017
Indirect via fruit/infructescence	-0.209	0.423	0.089	0.561	-0.284	-0.024	0.014	0.030	-0.158	0.032	0.153	-	-0.054	0.012
Indirect via fruit infructescence/plant	-0.153	0.190	0.038	0.023	-0.107	0.005	-0.016	0.038	-0.040	0.010	0.069	-0.061	-	-0.007
Indirect via Fruit brix	-0.175	-0.043	-0.013	-0.117	0.043	0.019	0.006	-0.003	0.056	-0.010	-0.065	0.062	-0.030	-
Total	0.639	-0.656	-0.306	-1.232	0.661	0.007	-0.119	0.271	0.080	-0.060	-0.066	0.351	-0.176	-0.004



Since fruit weight cannot be directly measured visually, focusing on the number of fruits per plant may be a more suitable trait for selecting tomatoes with higher fruit weight per plot. The moderately strong positive contribution of individual fruit weight, sepal height, and fruits per plant to fruit weight indicates that phenotypic improvements in these traits could enhance fruit weight and related characteristics, such as individual fruit weight per plot and fruit count per plant. The direct contribution of fruit produced per plant to the total fruit weight per plot was enhanced by the number of fruits per infructescence, fruit height, and the number of fruit infructescence per plant, although it was obscured by fruit diameter and sepal height. Sharma *et al.*, (2019) and Anuradha *et al.*, (2020) observed that a higher number of fruits on tomato plants correlates with increased fruit yield due to a significant association between these two traits. also, the negative impact of vine height at 50 % flowering, along with fruit per infructescence and fruit infructescence per plant, on fruit weight/plot was linked to the indirect effects of fruit diameter and sepal height. The residual effect explained 44% of the variability in the dependent variable, indicating the proportion accounted for by the causal factors (Sushma *et al.*, 2020). The independent traits explained a higher percentage variation, at 66 %, in fruit weight.

CONCLUSION AND RECOMMENDATION

The microclimatic factors played a significant role in determining the duration of fruit appearance and maturity, as well as influencing various parameters such as fruit length, width, total soluble solids (TSS), and fruit weight per plot. The variation observed among the genotypes indicates the potential for selecting promising cultivars suitable for cultivation within the Sudan agroecology. The Shukla stability variance and Wricke ecovalence revealed that 'TSU 04', 'TSU 02' and 'TSU 03' exhibited stable performance regarding TSS on year-to-year basis. Specifically, 'TSU 04', 'TSU 02' demonstrated stability in terms of fruit height, while 'TSU 01', 'TSU 06' and 'TSU 05' were stable for fruit width. Furthermore, 'TSU 02', 'TSU 04', 'TSU 06' and 'TSU 05' showed resilience to microclimate variations concerning fruit weight per plot. Improving individual fruit weight, sepal length, and the number of fruits per plant is likely to enhance overall fruit yield. Additionally, attributes such as fruit width and vine length during the flowering stage will further contribute to fruit yield outcomes. Nevertheless, the masking effect of fruit brix in the indirect pathway to fruit yield highlights the necessity for a balanced approach when selecting between the number of fruits per infructescence and the infructescence itself.

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