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Research article

Growth and Fruit morphometric characteristics of local avocado germplasm (*Persea americana* Mill.) grown in northern Tanzania

Iman S. Yangaza[a,*], Agnes M.S. Nyomora[b], Charles O. Joseph[c], Emmanuel M. Sangu[a], José I. Hormaza[d]

[a] *Department of Botany, University of Dar es Salaam, P.O Box 35060, Dar es Salaam, Tanzania*
[b] *St. Augustine University of Tanzania, P.O Box 307, Mwanza, Tanzania*
[c] *Department of Crop Science and Beekeeping Technology, University of Dar es Salaam, P.O Box 35143, Dar es Salaam, Tanzania*
[d] *Instituto de Hortofruticultura Subtropical y Mediterránea La Mayora (IHSM La Mayora-CSIC-UMA), Avda. Dr. Wienberg s/n, Algarrobo-Costa, 29750, Málaga, Spain*

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ABSTRACT

Tanzania has a diverse agroecological area suitable for growing tropical fruits, including avocados. In Northern Tanzania, avocados have been growing under variable soil and altitudinal characteristics for over 100 years, allowing the naturalisation of this crop in this region. However, the region's avocado germplasm is uncharacterised, thus impeding the selection of elite genotypes for increased value and breeding programmes. This study examined the growth and fruit morphometric characteristics of avocado populations grown under variable soil pH and altitude in six districts in the Tanga, Kilimanjaro and Arusha regions. Variations in growth and fruit morphometric characteristics were compared using a one-way analysis of variance (ANOVA). Pearson product-moment correlations (r) were used to evaluate the relationship between studied growth and fruit morphometric traits. A linear mixed-effects model (LMM) was used to assess the influence of the soil pH, altitude, tree height, canopy diameter, and trunk diameter on fruit length, fruit diameter, pulp thickness, and seed diameter. Principal Component Analysis (PCA) was used to depict the extent of the racial admixtures in the avocado germplasm in the Northern regions of Tanzania. The results revealed a significant variation in growth and fruit morphometric characteristics ($p < 0.05$). The Korogwe population had the highest tree height, while the Karatu had the lowest. Tree height was positively correlated with the trunk diameter ($r = 0.63$, $p < 0.001$. There was a positive correlation between fruit length and pulp thickness ($r = 0.51$, $p < 0.001$), fruit diameter and pulp thickness ($r = 0.47$, $p < 0.001$), and fruit length and fruit diameter ($r = 0.36$, $p < 0.001$). The fruit diameter was positively correlated with the seed diameter ($r = 0.61$, $p < 0.001$). There was a significant but weak association between fruit length and trunk diameter (−0.01), fruit length and canopy diameter (0.15), and between seed diameter and tree height (2.95e-2). These findings highlight the influence of individual tree genetic makeup on the variation in growth and fruit morphometric characteristics. The morphometric trait correlations may prove valuable in field measurements, especially when resources are limited. The study further indicates the presence of all avocado races within the local germplasm, highlighting its high diversity. Remarkably, the observed admixture of variant races implies gene flow among studied avocado populations, possibly facilitated by sharing seedlings among farmers or seed

* Corresponding author.
E-mail addresses: yangazaman@gmail.com (I.S. Yangaza), agnesnyomora@gmail.com (A. M.S. Nyomora), jcharles@udsm.ac.tz (C.O. Joseph), ihormaza@eelm.csic.es (J.I. Hormaza).

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disposal through avocado fruit trading. Further study is needed, particularly in quantifying the above-ground biomass of local avocados in northern Tanzania, potentially contributing to carbon credit initiatives for fruit crops..

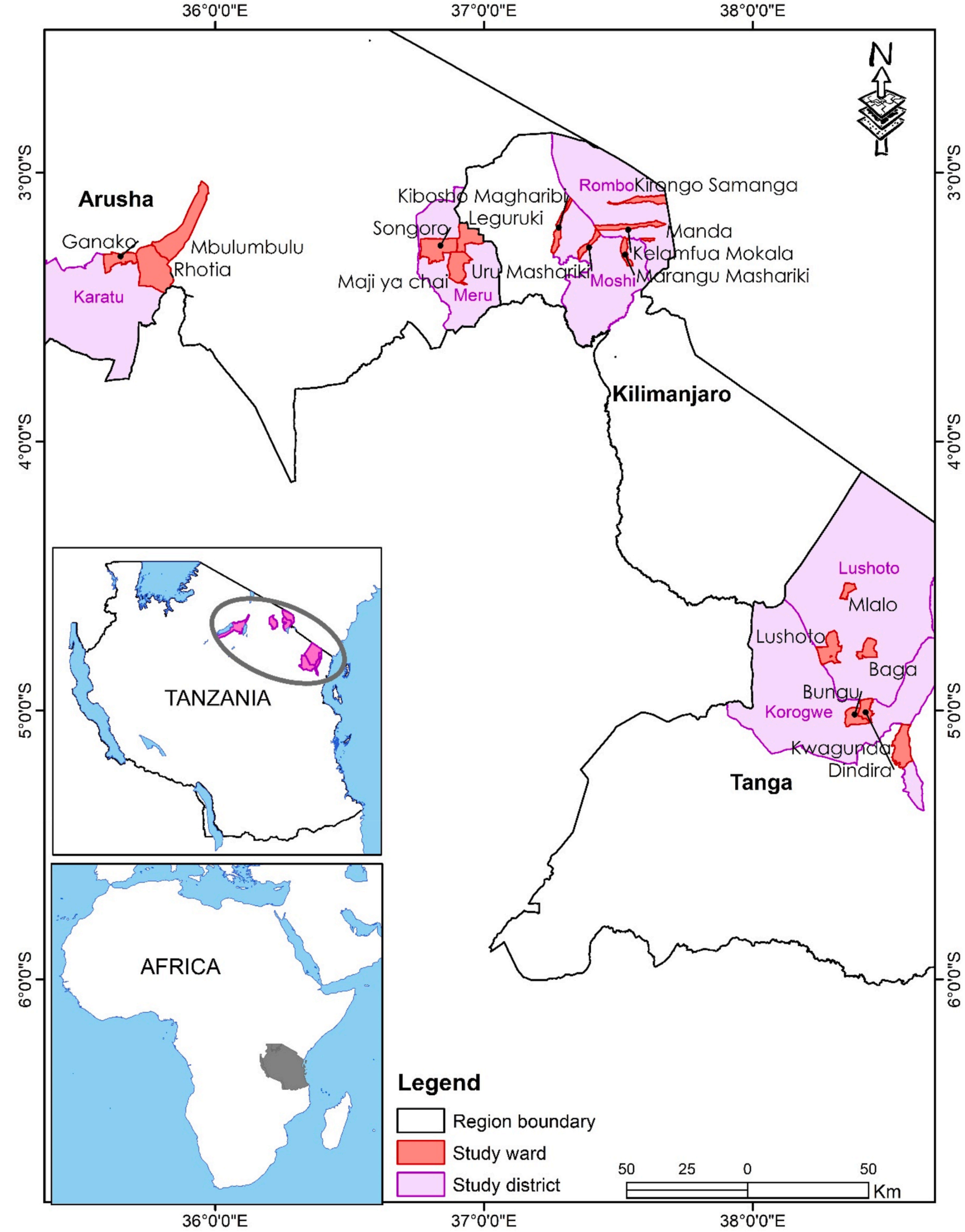

Fig. 1. Locations of the study areas.

1. Introduction

Fruits are primary sources of essential nutrients for humans and are significant drivers for sub-Saharan Africa's economic growth and development [1]. Avocado (*Persea americana* Mill.), a Lauraceae family member already consumed in Mesoamerica 10,000 years ago, is one of the first domesticated fruit crops [2]. Avocados are considered superfoods because they are rich in essential nutrients and phytochemicals, including fat-soluble vitamins (ADEK), high protein levels, potassium, omega-3, 6 fatty acids, and phenolic compounds [3]. These components have anticancer, antifungal, antitumor, antioxidant, cholesterol-reducing, and cardiovascular disease-preventive properties [4]. Avocado is a polymorphic species comprising at least eight botanical varieties or subspecies that have evolved under distinct edaphoclimatic conditions and geographical isolation. Among these, three horticultural races hold agronomic significance: *P. americana* var. *drymifolia*, *P. americana* var. *guatemalensis*, and *P. americana* var. *Americana*, commonly known as the Mexican, Guatemalan, and West Indian horticultural races, respectively, based on their presumed centers of origin [5]. These horticultural races primarily differ in botanical characteristics and edaphoclimatic preferences. Altitude is an essential factor that influences climatic conditions and soil characteristics, subsequently influencing variation in plant growth and performance [6]. While the Guatemalan and Mexican races, originated from highlands above 1000 masl, are better adapted to cooler subtropical climates, the former (from lower elevations) is more susceptible to low temperatures than the latter (from higher elevations). In contrast, the West Indian rage, originated in lowlands at 0–1000 masl [7]. The avocado tree grows to approximately 30 m tall, with a trunk diameter ranging from 30 to 150 cm. Despite that, the canopy diameter changes due to seasons and orchard management practices such as pruning, but generally, the canopy diameter ranges from low to dense [8]. Fruit morphometric traits (fruit length, diameter, seed diameter, and pulp thickness) are primarily influenced by fruit shape and seed shape. The fruit length ranges from 7 to 20 cm, and fruit diameter can reach up to 15 cm, but seed diameters range from 1 to 8 cm [9].

Avocado cultivation has been expanded worldwide to regions with tropical, subtropical, and Mediterranean climates. Tanzania has a diverse agroecological zone suitable for growing avocados. Avocados were first introduced in Moshi by the Evangelical Lutheran Church German Missionaries in the 1880s [10]. Since then, farmers have been sharing avocado seeds in establishing avocado orchards in Tanga, Kilimanjaro and Arusha regions. Thus, avocados in Northern Tanzania have been naturalised to form uncharacterised local avocado germplasm. Avocados in Northern Tanzania are haphazardly grown irrespective of their optimal climatic and altitudinal ranges, which may influence plant growth and productivity. However, this region contributes a significant bulk of avocado fruits in local and regional markets and serves as a dependable source of rootstock for grafting improved cultivars in the country. The available literature on avocado growth, especially tree allometry and fruit morphometric characteristics, is predominantly from commercial cultivars such as Hass, Fuerte, Pinkerton, Ettinger, Nabal, and Bacon [11]. Such information is missing for the local avocado germplasm of Northern Tanzania. The lack of such information constrains the effective utilisation of local avocados for breeding and the opportunity for value addition.

Literature shows that tree growth varies enormously in height, trunk diameter, and canopy diameter. Data capturing the relationship between tree height, trunk diameter, and canopy diameter of trees have been used to test the theory linking tree body size and metabolism across ecological scales [12]. In addition, growth morphometric characteristics are widely used to estimate plant biomass and productivity [13]. In this regard, assessing tree growth is essential to numerous lines of ecological and physiological research [14]. On the other hand, the northern Tanzania germplasm possesses significant variations in fruit morphometric traits. Such variation has been influencing farmers' decisions on fruit and seedling selection. Describing the fruit's morphometric traits is essential in understanding the distribution and diversification [15] of the avocado in the region. It was hypothesised that the selective selection of seedlings based on fruit morphometric traits among farmers influences the distribution, diversification, and management of avocado germplasm in the region.

Therefore, this study analysed growth and fruit morphometric characteristics of local avocado germplasm grown in northern Tanzania by assessing variations in growth parameters and fruit morphometrics under different soil pH and altitude. This study reports on the variation of growth and fruit morphometric characteristics and their relationship with the effective utilisation and management of local avocado germplasm in northern Tanzania.

2. Material and methods

2.1. Description of the study area

This study was conducted in Northern Tanzania regions' in Tanga, Kilimanjaro, and Arusha. Two districts were selected in each region, including Korogwe and Lushoto in the Tanga region, Rombo and Moshi DC in Kilimanjaro, and Meru and Karatu in Arusha (Fig. 1), to make a total of six districts. The district's inclusion was based on the availability of large volumes of the local avocado germplasm relative to another district in the region. The Tanga region lies between latitude 4°40′ to 5°53′ in the south and longitude 37°02′ to 39°12′ in the east. It covers a total area of 26,700 km^2 and has a population of 2,615,597 [16]. The mean annual minimum and maximum temperatures are 25.1 °C and 31.6 °C, respectively, and the mean annual rainfall is 1448.3 mm [17]. Kilimanjaro region is located between latitudes 2°51′ and 4°35′ S and longitudes 37°08′ and 38°05′ East. It covers an area of 13,300 km^2 and has a population of 1,861,934 [16]. The mean annual minimum and maximum temperatures are 17.8 °C and 30.6 °C, respectively, and the mean annual rainfall is 517.4 mm [17]. The Arusha region lies between latitude 1°41′ to 3°29′ South and longitude 35°14′ to 37°03′ East. It covers an area of 37,600 km^2 and has a population of 2,356,255 [16]. The mean annual minimum and maximum temperatures are 15.1 °C and 26.2 °C, respectively, and the mean annual rainfall is 883.9 mm [17]. Specific average temperature and precipitation at the district level were respectively: 23.8 °C and 1271 mm in Korogwe, 19.9 °C and 1377 mm in Lushoto, 21.2 °C and 762 mm in Rombo, 22.3 °C and 2389 mm in Moshi, 7.8 °C and 837 mm in Meru, and 18.4 °C and 1679 mm in Karatu. The local avocado germplasm used in this study was seed-propagated growing in soil with soil pH ranges from 4.7 to 7.2 and altitude ranges from 301 to 1967 masl.

2.2. Data collection

This study was conducted in 2021 and sampled homegrown avocado trees around smallholder farmer's homesteads. The samples from each district were collected from three wards and purposively selected based on the number of avocado trees present. Each ward consisted of three villages from which five morphologically different avocado trees aged over ten years were sampled per village, totalling 270 samples. Local avocados are considered mature, with maximum production when aged between 10 and 15 years, and may continue to produce for up to 50 years [18]. Thus, individual tree age was not included in the analysis as a factor for growth and fruit morphometrics. A minimum distance of approximately 300 m was adopted from one farmer's household to another to minimise the homogeneity of information. The height of the avocado tree was measured in metres from the tree base and was estimated using a graduated pole [19]. The average canopy diameter was measured in meters using a tap measure in two dimensions of the canopy (widest and narrowest parts) [20]. The diameter of the avocado tree trunk was derived from the Circumference at Breast Height (CBH) measured in centimetres using a tap measure. Fruit morphometric data were recorded from three mature avocado fruits collected from each tree. Fruit morphometric data were collected across all districts during the low-peak season to get the maximum growth size of the fruit [21]. All sampling sites were georeferenced using a Garmin GPSMAP® 66sr gadget, and altitudes were recorded as meters above sea level (masl). A Vernier calliper was used to measure fruit length, diameter, seed diameter, and pulp thickness. Fruit diameter, seed diameter, and pulp thickness were measured from the fruit's equatorial position [22]. The soil samples were collected in a three-point radius of 1 m from the tree trunk, at a depth of 30 cm using a soil auger, and then mixed to get a composite sample. Soil pH was determined by soil-water mixture protocol and was analysed by the Tanzania Agricultural Research Institute (TARI), Mlingano Soil Laboratory.

2.3. Data analysis

Growth and fruit morphometric measurements were recorded in an Excel spreadsheet, and all statistical analyses were performed on a population basis using R version 4.3.2 [23]. The descriptive analysis of the quantitative variables is presented as mean, minimum, and maximum values. Before analysis, data were first checked for normality assumptions using the standard plots in R package ggplot2 [24] and the Shapiro–Wilk test, whereas homoscedasticity was tested using the Levene Test. Data that did not obey normality at $\boldsymbol{\alpha} = 0.05$ were transformed, and the best transformation method was checked using the bestNormalize R package [25].

Variations in tree height, trunk diameter, canopy diameter, fruit length, diameter, pulp thickness, and seed diameter were compared using a one-way analysis of variance (ANOVA), presented in mean with standard error of the mean (Mean ± SEM). ANOVA was performed using the general linear model, and avocado populations (districts) were used as a factor. The Tukey honestly significant difference post hoc test (Tukey's HSD) test was used to compare means wherever significant differences were observed at a significance level of $p < 0.05$. Pearson product-moment correlations (r) were used to evaluate the relationship between studied growth and fruit morphometric traits using the Hmisc R package [26]. A linear mixed-effects model (LMM) assessed the influence of the soil pH, altitude, tree height, canopy diameter, and trunk diameter on fruit length, fruit diameter, pulp thickness, and seed diameter. This LMM used soil pH, tree height, canopy diameter, and trunk diameter as fixed effects. To control for any spurious effects in the fruit, morphometric variables that could arise from fixed effect variables, altitudes, and districts (populations) were employed as random effect variables. The LMMs equations were computed using the lme4 R package [27]. To supplement the observed variations in growth and fruit morphometrics, the Principal Component Analysis (PCA) was used to display the presence of admixtures of sampled avocado trees among the studied districts. The PCA was computed using the FactoMineR [28] and factoextra [29] R packages.

Table 1
Variation of altitude and soil pH among avocado growing populations in northern Tanzania.

Population	Altitude	Soil pH
Karatu	1604.20 ± 4.83^{a}	6.58 ± 0.03^{a}
Korogwe	951.72 ± 21.17^{b}	6.03 ± 0.03^{b}
Lushoto	1324.83 ± 21.38^{c}	6.11 ± 0.05^{b}
Meru	1483.78 ± 10.14^{ad}	6.69 ± 0.02^{a}
Moshi	1402.38 ± 15.52^{cd}	5.91 ± 0.03^{b}
Rombo	1484.33 ± 13.85^{ad}	6.17 ± 0.03^{b}
***F*-value**	35.33	17.43
***p*-value**	<0.001	<0.001

Values in each column are presented as Mean ± SEM, and differences in superscript letters of the mean in each column are statistically significant at $p < 0.05$.

3. Results

3.1. Altitude and soil pH variations in the avocado growing areas in northern Tanzania

The altitude and soil pH differed significantly ($p < 0.001$ for both parameters) among the studied avocado populations (Table 1). The highest altitude (1604.2 ± 4.83) was recorded for the Karatu population, whereas the lowest (951.72 ± 21.17) was recorded for the Korogwe population. Soil pH values were slightly acidic to nearly neutral for Meru (6.69 ± 0.02) and Karatu (6.58 ± 0.03). Additionally, no significant correlation between altitude and soil pH in the avocado-growing areas in northern Tanzania was observed. The overall means for altitude and soil pH were 1375 m and 6.2 m, respectively.

3.2. Growth characteristics of local avocados grown in northern Tanzania

The growth characteristics of sampled avocado trees differed significantly between the avocado populations in Northern Tanzania (Table 2). The tree height differed significantly between populations ($p < 0.001$), with the Korogwe population having the highest tree height (14.74 ± 0.33) and the Karatu population having the lowest (9.44 ± 0.17). There was a significant difference in the trunk diameter among the populations ($p < 0.01$), with the Moshi population having a larger diameter (152.2 ± 4.42) and the Karatu population having a smaller diameter (104.43 ± 2.23). There was no significant difference in avocado canopy diameter among the studied avocado populations. The overall means for tree height, canopy diameter, and tree trunk diameter were 12.6 m, 8.1 m, and 125.1 cm, respectively.

Moreover, positive correlations were obtained between canopy diameter and height ($r = 0.49$, $p < 0.001$). There was a positive correlation between canopy and trunk diameter ($r = 0.70$, $p < 0.001$). Tree height was positively correlated with the trunk diameter ($r = 0.63$, $p < 0.001$) (Table 3).

3.3. Fruit morphometric characteristics of local avocado grown in northern Tanzania

Fruit length, fruit diameter, seed diameter, and pulp thickness of the local avocado populations in northern Tanzania differed significantly at $p < 0.05$ (Table 4). For fruit length, the highest value was recorded in the Karatu population (11.18 ± 0.15 cm), while the shortest fruit length was present in the Lushoto population (9.36 ± 0.11 cm). The most significant value for fruit diameter was obtained in the Rombo population (8.43 ± 0.08 cm), whereas the lowest was recorded in the Meru population (7.54 ± 0.08 cm). For pulp thickness, the highest values were obtained in the Korogwe (1.50 ± 0.03 cm) and Rombo (1.56 ± 0.02 cm) populations, whereas the lowest value 1.27 ± 0.02 cm) was recorded in the Meru population. In contrast, seed diameter did not differ significantly among the populations ($p > 0.05$). The mean fruit length, diameter, fruit diameter, seed diameter, and pulp thickness were 10.5 cm, 7.9 cm, 4.9 cm, and 1.4 cm, respectively.

There was a significant correlation in some of the fruit morphometrics of avocado populations from northern Tanzania (Table 5). There was a positive correlation between fruit length and pulp thickness ($r = 0.51$, $p < 0.001$), fruit diameter and pulp thickness ($r = 0.47$, $p < 0.001$), fruit diameter and length ($r = 0.36$, $p < 0.001$) and fruit diameter and seed diameter ($r = 0.61$, $p < 0.001$). However, no significant correlation was observed between seed diameter and pulp thickness ($r = 0.05$, $p > 0.05$) and seed diameter and fruit length ($r = -0.02$, $p > 0.05$).

3.4. The association between soil pH, tree height, trunk, and canopy diameter on the fruit length, fruit diameter, seed diameter, and pulp thickness of avocados grown in northern Tanzania

Soil pH and studied growth characteristics were significantly associated with fruit morphometrics (Table 6). A positive association was found between fruit length and canopy diameter ($t = 2.43$, $p < 0.05$). In contrast, a negative association was obtained between fruit length and trunk diameter ($t = -2$, $p < 0.05$). There was a positive association between seed diameter and tree height ($t = 2.09$, $p = 0.05$). In addition, none of the tested fixed effects had a significant association with fruit diameter and pulp thickness.

Moreover, a principal component analysis (PCA) revealed an admixture pattern among sampled avocado trees (Fig. 2).

Table 2
Variation of growth characteristics among avocado populations in northern Tanzania.

Population	Tree height	Trunk diameter	Canopy diameter
Karatu	9.44 ± 0.17^{a}	104.43 ± 2.23^{a}	7.74 ± 0.16^{a}
Korogwe	14.74 ± 0.33^{b}	121.98 ± 3.79^{ab}	9.10 ± 0.24^{a}
Lushoto	12.52 ± 0.35^{bc}	122.08 ± 3.64^{ab}	8.01 ± 0.19^{a}
Meru	11.59 ± 0.24^{ac}	130.24 ± 3.06^{ab}	7.52 ± 0.19^{a}
Moshi	14.17 ± 0.30^{bc}	152.20 ± 4.42^{b}	8.43 ± 0.22^{a}
Rombo	12.86 ± 0.41^{bc}	119.49 ± 2.44^{ab}	7.74 ± 0.13^{a}
***F*-value**	6.41	3.67	1.55
***p*-value**	<0.001	<0.01	>0.05

Values in each column are presented as Mean ± SEM, and differences in superscript letters of the mean in each column are statistically significant at $p < 0.05$.

Table 3
Pearson correlation coefficients of growth characteristics among the avocado populations in northern Tanzania.

Variables	Canopy diameter (m)	Tree height (m)
Tree height (m)	0.49***	
Trunk diameter (cm)	0.70***	0.63***

****Significant at $p < 0.001$.*

Table 4
Variation in fruit morphometrics among the avocado populations in northern Tanzania.

Population	Fruit length	Fruit diameter	Pulp thickness
Karatu	11.18 ± 0.15^{a}	7.89 ± 0.06^{ab}	1.46 ± 0.02^{ab}
Korogwe	10.74 ± 0.16^{ab}	7.76 ± 0.09^{ab}	1.50 ± 0.03^{b}
Lushoto	9.36 ± 0.11^{b}	7.77 ± 0.07^{ab}	1.37 ± 0.02^{ab}
Meru	10.19 ± 0.13^{ab}	7.54 ± 0.08^{a}	1.27 ± 0.02^{a}
Moshi	10.29 ± 0.14^{ab}	8.03 ± 0.06^{ab}	1.37 ± 0.02^{ab}
Rombo	11.07 ± 0.14^{a}	8.43 ± 0.08^{b}	1.56 ± 0.02^{b}
***F*-value**	3.92	2.73	3.63
***p*-value**	<0.01	<0.05	<0.01

Values in each column are presented as Mean ± SEM, and differences in superscript letters of the mean in each column are statistically significant at $p < 0.05$.

Table 5
Pearson correlation coefficients for fruit morphometrics among the avocado populations in northern Tanzania.

Variables	Pulp thickness	Fruit length	Fruit diameter
Fruit length	0.51***		
Fruit diameter	0.47***	0.36***	
Seed diameter	0.05	−0.02	0.61***

**** Significant at $p < 0.001$.*

Table 6
The association between soil pH, canopy diameter, tree height, and trunk diameter on fruit length, fruit diameter, seed diameter, and pulp thickness of the sampled local avocado populations grown in northern Tanzania.

Fruit morphometrics	Edaphic factors	Estimate	Std. Error	t value	Pr (>|t|)
Fruit length	(Intercept)	7.99	1.79	4.47	1.24e-05
	Soil pH	0.37	0.27	1.37	0.17
	Canopy diameter	0.15	0.06	2.43	0.02 *
	Tree height	−0.002	0.04	−0.08	0.94
	Trunk diameter	−0.01	0.004	−2.00	0.04 *
Fruit diameter	(Intercept)	7.17e+00	9.67e-01	7.41	2.98e-12
	Soil pH	1.10e-01	1.45e-01	0.76	0.45
	Canopy diameter	−2.64e-03	3.43e-02	−0.08	0.94
	Tree height	9.21e-03	1.91e-02	0.48	0.63
	Trunk diameter	−3.46e-04	2.21e-03	−0.16	0.88
Pulp thickness	(Intercept)	1.918e+00	2.89e-01	6.63	3.03e-10
	Soil pH	−7.58e-02	4.34e-02	−1.75	0.08
	Canopy diameter	1.12e-02	1.03e-02	1.09	0.28
	Tree height	1.16e-03	5.73e-03	0.20	0.84
	Trunk diameter	−1.01e-03	6.63e-04	−1.53	0.13
Seed diameter	(Intercept)	3.678e+00	7.09e-01	5.18	5.66e-07
	Soil pH	1.913e-01	1.06e-01	1.80	0.07
	Canopy diameter	−4.12e-02	2.54e-02	−1.62	0.11
	Tree height	2.95e-02	1.42e-02	2.09	0.04 *
	Trunk diameter	6.82e-04	1.63e-03	0.42	0.68

** Significant at $p < 0.05$.*

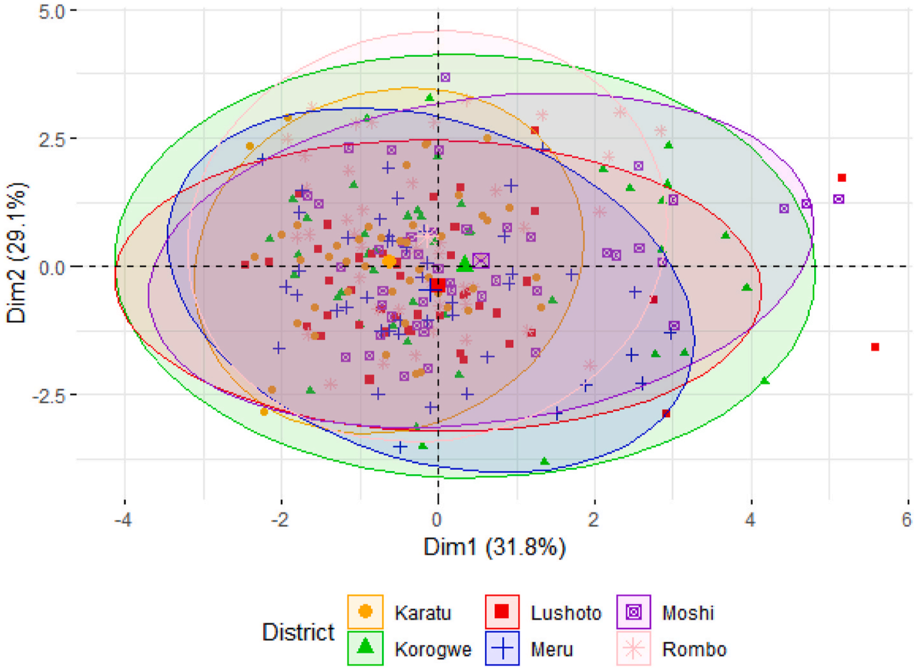

Fig. 2. The PCA showing the presence of admixture based on growth and fruit morphometrics of the 270 sampled avocado trees in six districts of northern Tanzania.

Additionally, most of the sampled avocado trees across all studied populations were grouped irrespective of their district of origin.

4. Discussion

4.1. Altitude and soil pH variations in the avocado growing areas in northern Tanzania

The study sites are in the western Usambara, Kilimanjaro, and Meru mountains, each characterised by distinct landscapes, climatic conditions, and soil characteristics. A total of 6 populations were studied, one for each district (Karatu, Korogwe, Lushoto, Meru, Moshi, and Rombo). The Karatu population recorded the highest altitude at 1498 m, while the Korogwe population had the lowest at 301 m. Geographically, Karatu is located in the highlands, and its landscape is relatively uniform compared to Korogwe, which exhibits both high and low elevations.

The soil pH of the Karatu and Meru populations was nearly neutral, in contrast to the slightly acidic pH observed in the other districts. Various factors, such as types of parental rocks, weathering processes, precipitation, and agricultural practices, may influence soil pH [30]. Among these factors, the application of synthetic fertilisers and the build-up of soil organic matter can affect soil pH, especially in intensive farming systems [31]. Karatu, known for significant vegetable, pigeon, and green pea production, and Meru, renowned for intensive vegetable farming, particularly carrots, both maintain a soil pH within the optimal range of 6–7.5 for leguminous and carrot farming [32,33]. Therefore, the higher soil pH in Karatu and Meru populations may be attributed to agricultural practices involving fertiliser application and the relatively similar parental rock compared to the rest of the studied avocado populations.

4.2. Growth characteristics of avocados grown in northern Tanzania

Tree height is a critical allometric characteristic that signifies a tree's ability to compete for light and indicates the tree's life history, productivity, and resilience to various environmental conditions [34]. The Korogwe population exhibited the highest tree height, while the Karatu population displayed the lowest. Genetic-environment interaction is pivotal in tree morphometric variations and genetic selection [35]. Korogwe experiences relatively warm (23.8 °C) and humid conditions compared to Karatu, which encounters prolonged cold (18.4 °C) and dry periods. Temperature and other climatic conditions significantly influence tree height increase [36]. Moreover, in Korogwe sampling sites, avocados were often intercropped with timber trees like Pinus and Eucalyptus, which enhanced competition for resources, including sunlight, favouring height growth [36]. The genetic makeup of sampled avocado trees, differences in tree age, temperature variations between populations, and competition for sunlight due to intercropping might collectively contribute to the observed difference in tree height between Korogwe and Karatu populations. Therefore, Korogwe avocado trees may derive more ecological and physiological benefits than those in the Karatu population. Furthermore, this study's mean tree height of avocados was 12 m. According to Ref. [9], avocado trees with heights exceeding 5 m are considered mature, while those ranging from

3.5 to 4 m are relatively easier to manage and more productive than taller ones. Thus, based on the tree height of sampled avocados grown in northern Tanzania, avocado orchards might lack proper management practices, such as pruning, insecticide, and pesticide application.

Stem size is another allometric characteristic providing valuable information about biomass volume, plant health, the competitive position of a tree, and suitable management practices [37]. Trunk diameter significantly differed between the Moshi and Karatu populations, with Moshi exhibiting a larger diameter. Stem growth is primarily influenced by the tree's genetic makeup and environmental interactions, changing due to seasonal and diurnal fluctuations [38]. Although soil pH is a crucial factor influencing mineral nutrient availability for plant growth, including stem growth, both Moshi and Karatu populations had slightly acidic soil, ideal for avocado growth. The observed difference in trunk diameter might be attributed to variations in tree age, as avocados were first introduced in Moshi in the 1880s, suggesting that most trees in this population might be older than those in the Karatu population [10]. The influence of age difference on stem size was also noted among avocado trees in Indonesia, where aged avocados exhibited a larger trunk diameter [39]. Despite this, genetic differences between sampled avocados in Moshi and Karatu populations might contribute to the observed difference in stem size. Therefore, based on the difference in trunk diameter between the Moshi and Karatu populations, avocados from Moshi might exhibit higher physiological performance, including fruit yield, than those from the Karatu population. Generally, the mean trunk diameter of sampled avocados in northern Tanzania was 125.1 cm. The trunk size values suggest that sampled avocados from northern Tanzania have a considerable stem size, indicating healthy and productive trees.

Tree growth and productivity depend significantly on canopy diameter, a main controlling factor for leaf area index (LAI) and a key driver in capturing and converting sunlight energy into biomass productivity [40]. The present study found no significant difference in avocado canopy diameter among the studied populations. Avocado canopy architecture is primarily genetically controlled, influenced by branching systems that determine canopy diameter and can be modified by orchard management practices, such as pruning [41]. Local avocados in the studied populations are grown in intercropping agricultural systems, involving frequent pruning to allow sunlight to reach other crops underneath. The mean canopy diameter of the sampled avocados from northern Tanzania was 8.1 m. Although this study did not measure other critical determinants for maximum light interception, such as LAI and leaf area distribution, the mean canopy diameter suggests a potential for local avocados from northern Tanzania to have a higher capacity for total light interception and, consequently, higher fruit yield.

Moreover, positive correlations were found between canopy diameter and tree height, as well as between canopy diameter and trunk diameter. Additionally, tree height positively correlated with trunk diameter (Table 3). The close growth rates observed have likely influenced the positive relationship among avocado tree height, trunk diameter, and canopy diameter [20]. The relationship between tree morphometric characteristics provides key knowledge for orchard management as they affect economically relevant parameters, such as tree water needs, fruit quality, and yield [42]. This relationship between the studied tree morphometric characteristics of sampled avocado trees from northern Tanzania implies that the information could be valuable for orchard management practices and breeding activities to achieve high-quality fruit yield.

4.3. Fruit morphometric characteristics of avocado grown in northern Tanzania

Significant variations were observed in fruit length, diameter, and pulp thickness among local avocados in northern Tanzania.

Fruits in the Karatu and Rombo populations exhibited significantly greater length than those in the Lushoto population. Fruit length, a trait primarily governed by genetics, indicates distinct genetic differences between the avocados of Karatu and Rombo populations and those of Lushoto. Furthermore, as fruit length often corresponds to customer-appealing features, the longer fruits from Karatu and Rombo populations may have a competitive advantage in the market [43]. Notably, longer fruits are characteristic of avocados from West Indian races, while smaller to medium-sized avocados are typical of Mexican and Guatemalan races [44]. This diversity suggests that the northern Tanzania germplasm encompasses avocados representing both avocado races.

The Rombo population also displayed a significantly wider fruit diameter than the Meru population, which had the narrowest. Fruit diameter, influenced by genetic and environmental interactions governing pulp deposition and seed growth [45], showcases distinct genetic differences between the Rombo and Meru populations. Genetic variations have been reported to impact fruit diameter in avocados grown in various regions, including the eastern mid-hills of Nepal [46] and Ethiopia [18]. The Rombo population's avocados, characterised by longer and wider fruits, may harbour elite trees for breeding programs, as larger fruit sizes tend to attract customer preference.

Additionally, pulp thickness in the Korogwe and Rombo populations was significantly greater than in the Meru population, which exhibited the smallest pulp thickness. Genetic-environmental interactions during fruit growth significantly influence pulp deposition, suggesting that genetic makeup is crucial in the observed differences among populations. Consistent with findings in the eastern mid-hills of Nepal, avocado genetic makeup was identified as a primary factor influencing pulp thickness variation [46]. Therefore, with their greater pulp thickness, avocados from the Korogwe and Rombo populations have a higher likelihood of customer preference than other studied populations.

The seed diameter of avocado fruits did not show significant differences among populations, with a mean seed diameter of 4.9 cm. Seed diameter primarily influences seed size, a crucial factor for seedling germination and growth [47]. The observed mean seed diameter suggests that the local germplasm in northern Tanzania harbours seeds with potential applications in the grafting industry and value additions.

Significant correlations were found among the fruit morphometrics of studied avocados. Pulp thickness exhibited positive correlations with fruit length and diameter, while fruit diameter also showed a positive correlation with seed diameter. Understanding the direction of these correlations aids in establishing a fruit maturity index [48]. These positive correlations, resulting from proportional cell increase during fruit development [49], align with findings in Ethiopia's Hass, Fuerte, Ettinger, and Nabal [18]. The observed fruit morphometric correlations in local avocados from northern Tanzania could prove valuable for fruit maturity indexing and guide future breeding programs.

4.4. The relationship between soil pH, tree height, trunk diameter, and canopy diameter on the fruit length, fruit diameter, pulp thickness, and seed diameter of sampled avocados grown in northern Tanzania

Positive associations were observed between canopy diameter and fruit length, while a negative association was found between tree diameter and fruit length. Additionally, a positive association existed between seed diameter and tree height. Despite these associations, it is essential to note that the observed relationships demonstrated relatively weak strength based on the coefficient estimates. Avocado fruit size is predominantly influenced by gene expression mediated through intricate hormonal and metabolic interactions [45]. While external applications of growth promoters like CPPU and GA have been reported to increase Hass fruit size [50], the findings imply that trees' genetic makeup significantly shapes the fruit morphometric characteristics of avocados from northern Tanzania. It is crucial to emphasise the need for data spanning multiple production seasons to confirm the influence of environmental and climatic conditions on the fruit morphometric characteristics of the studied local avocado populations.

Furthermore, Principal Component Analysis (PCA) uncovered a morphometric admixture among the studied avocado trees. Most sampled avocado trees, irrespective of their specific sampling sites, were grouped together. This suggests a substantial gene flow facilitated by the exchange of seedlings among farmers or the haphazard disposal of seeds through fruit trading activities. Notably, this admixture pattern aligns with the study's findings, indicating that despite varying environmental and climatic conditions among the avocado populations, a significant portion of sampled avocados share close genetic relationships based on the studied tree and fruit morphometric characteristics.

5. Conclusion

The morphometric characteristics of local avocado trees in northern Tanzania displayed significant variations, indicating significant diversity within the germplasm. While mean values reflect healthy and productive trees, high tree heights suggest potential deficiencies in orchard management practices such as pruning and pesticide application. The observed relationships between morphometric characteristics provide valuable insights for effective orchard management and future breeding programs focused on enhancing fruit yield and quality. Furthermore, the distinct differences in fruit length, diameter, and pulp thickness among local avocados highlight the potential presence of elite trees within the germplasm, which is crucial for future breeding initiatives. The larger fruit sizes observed in most avocado fruits contribute positively to marketability. The study also emphasised the significant potential of mean seed diameter for rootstock supply and value addition. A notable positive correlation among fruit morphometrics suggests the utility of this information for fruit maturity indexing. Based on fruit morphometric characteristics, the study identified the presence of all avocado races within the studied populations, emphasising the genetic diversity present in the area studied. Weak associations between soil pH, tree allometry, and fruit morphometric characteristics underscore the dominant influence of genetic makeup on morphometric variations. Additionally, the study revealed significant admixture among avocado trees, indicating gene flow facilitated by the sharing of seedlings among farmers and the movement of seeds through trading. Future research should focus on quantifying above-ground biomass for local avocados in northern Tanzania, contributing to potential carbon credit initiatives for fruit crops. Furthermore, conducting a more extended study over multiple years is recommended to establish robust models for local avocado morphometric characteristics.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Agnes M.S. Nyomora: Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation, Conceptualization. **Charles O. Joseph:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Emmanuel M. Sangu:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **José I. Hormaza:** Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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