Gender-disaggregated Farmers Participatory Variety Selection in Amaranth Multilocation Trials in Kenya and Tanzania

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ADDITIONAL INDEX WORDS. ***Amaranthus cruentus*, *Amaranthus dubius*, *Amaranthus hypochondriacus*, additive main effects and multiplicative interaction (AMMI), genotype × environment, GGE biplot, mega-environment, organoleptic taste test, product profile**

ABSTRACT. **Amaranths (*Amaranthus* sp.) are a popular leafy vegetable grown and consumed by resource-poor people in many African countries. Greater awareness of the importance of nutritious foods has increased demand by African consumers for amaranth. Presently, most African farmers grow low-yielding local varieties of variable seed quality. High-yielding amaranth varieties that are adapted to the major agro-ecologies of eastern and southern Africa possess key traits needed by male and female farmers and meet diverse market preferences are required. The objective of this study was to identify amaranth lines adapted to major amaranth production environments in Kenya and Tanzania using a gender-disaggregated farmers participatory approach to explore possible gender differences in trait and variety preferences. Twenty amaranth entries were evaluated for vegetable yield, agronomic traits, and organoleptic taste tests in replicated, farmer-participatory variety selection trials at one location in Kenya and at four locations in Tanzania. Differences among entries (G), locations (E), and G × E interaction were significant or highly significant for marketable vegetable yield. Location followed by entry was the most important factor that explained differences in yield. G and G × E interaction biplot analysis classified the five locations into two different mega-environments, mainly based on altitude, temperatures, and soil characteristics. Marketable vegetable yield was positively correlated with leaf length, plant height, and the selection scores of female and male farmers at almost all locations. Selection scores of female and male farmers were positively correlated, indicating that male and female farmers shared similar amaranth variety preferences. Farmers identified and ranked important traits that can be used by breeders to design amaranth product profiles and develop amaranth breeding objectives. Lines combining high yield with high farmer and consumer preference scores have been retained for distinctiveness, uniformity, and stability tests for possible release as commercial varieties.**

Amaranth (*Amaranthus* sp.) is one of a few non-grass C_4 crop species that, even when their stomata are partially closed, maintain relatively high carbon dioxide fixation rates (National Research Council, 1984; Stallknecht and Schulz-Schaeffer, 1993). C_4 plants perform better than C_3 plants under adverse conditions, such as drought and high temperatures (National Research Council, 1984).

Amaranth was first domesticated in the Americas (Sauer, 1950, 1967) and is now grown worldwide as a leafy vegetable and/or grain crop. Amaranth is one of the most popular leafy vegetables in many African countries, and interest in amaranth grain is also increasing due to its high nutritional value (Achigan-Dako et al., 2014). As a vegetable, amaranth has been mainly grown and consumed by resource-poor people in rural areas (Rastogi and Shukla, 2013), but its popularity and consumption is increasing in periurban and urban areas because of rising awareness of its high nutritional value (Chelang'a et al., 2013), which has often been overlooked and underexploited.

Amaranth leaves are rich in iron, zinc, and calcium (Chakrabarty et al., 2018) and contain high-quality protein high in essential amino acids (Sarker et al., 2017), dietary fiber (Sarker et al., 2018a), and vitamins C and E (Sarker et al., 2015a). Amaranth leaves are also inexpensive sources of natural antioxidants, such as phenolics and flavonoids (Sarker and Oba, 2019a, 2019b, 2020a), and beta-carotene (Sarker et al., 2018a), with high antioxidant capacity (Sarker et al., 2020). Amaranth leaves also contain important and unique antioxidant pigments, such as betacyanins and betaxanthins (Sarker and Oba, 2020b), amaranthine and betanin (Sarker and Oba, 2020c), and carotenoids (zeaxanthin, neoxanthin, violaxanthin, and lutein) (Sarker and Oba, 2021). Amaranth grain is gluten free and is known for its high lysine content (Jimoh et al., 2018). Amaranth production in Africa is limited by the lack of improved varieties adapted to diverse production environments varying in altitude, temperature, rainfall, and other factors. Product profiles (traits sought by farmers, consumers, and other value chain actors) are critical for the identification of suitable varieties and for identification and ranking of breeding objectives (Ragot et al., 2018). Product profiles for amaranth are not well established, and the design of sound product profiles requires extensive interactions with farmers and other stakeholders. Only a few amaranth varieties have been released for commercial production in sub-Saharan Africa (Dinssa et al., 2016), and the varietal replacement rate is very slow. For example, the first amaranth variety in Tanzania was released in 2011, and the second was not released until 2018–19. Breeding and release of well-adapted improved varieties with key market-demanded traits are essential to realize farmer adoption, increased productivity gains, and increased amaranth supplies and consumption. Varieties

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922
4.8824	lb/ft^2	$kg \cdot m^{-2}$	0.2048
1.6093	mile(s)	km	0.6214
2.2417	ton(s)/acre	$t \cdot ha^{-1}$	0.4461
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

adapted to diverse environments and matching consumer preferences must undergo rigorous evaluation using farmer and consumer participatory approaches in diverse production environments. Farmer participatory plant breeding or variety selection has been used especially in marginal crops and environments as an important approach to identify varieties adapted to different environments and the needs of different end-users (Adeniji and Aloyce, 2013; Dinssa et al., 2020; Fufa et al., 2010; Ndinya et al., 2020). It is important to consider gender preferences in variety selection because there may be gender differences in trait preferences and rankings (Mehar et al., 2017). Gender-disaggregated participatory maize (*Zea mays*) variety trials conducted in Benin, Nigeria, and Mali identified gender-shared and distinct varietal traits (Tegbaru et al., 2020).

Dinssa et al. (2019) reported high differential performance of amaranth lines across Tanzanian environments differing in mean temperatures, rainfall, soil types, and other factors and identified two mega-environments: relatively high-altitude cool environments and coastal and low-altitude environments characterized by high temperatures. This indicated the need to select varieties adapted to each of the two contrasting mega-environments identified as target selection areas in Tanzania. The objective of the current study was to identify amaranth lines adapted to major amaranth production environments in Kenya and Tanzania using a gender-disaggregated farmers participatory approach to explore possible gender differences in trait and variety preferences.

Received for publication 27 Sept. 2021. Accepted for publication 28 Feb. 2022.

Published online 31 March 2022.

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This work received financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned and administered through the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) Fund for International Agricultural Research (FIA), grant number 81218429; and long-term strategic donors to the World Vegetable Center: Taiwan, UK aid from the UK government, United States Agency for International Development (USAID), Australian Centre for International Agricultural Research (ACIAR), Germany, Thailand, Philippines, Korea, and Japan. We acknowledge Raphael Mallogo and Mary Matovolwa for their assistance in field operations and data collection.

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https://doi.org/10.21273/HORTTECH04963-21

Materials and methods

Genetic materials. A total of 18 amaranth lines and two varieties (entries hereafter) were evaluated in multilocation trials (Table 1). The species of the entries in the study are purple/red amaranth or bush greens [*Amaranthus cruentus* (Grubben, 2004a)], spleen amaranth [*Amaranthus dubius* (Grubben, 2004b)], and prince's feather [*Amaranthus hypochondriacus* (Jansen, 2004)].

Entries evaluated in the study included lines developed by hybridization and selection and lines developed by single plant or mass selection from germplasm accessions. At the time the study was designed, AM6 (Table 1) was under evaluation by the Tanzania Official Seed Certification Institute for release in Tanzania; it was included in the study to assess its potential as a variety and to confirm its acceptance by farmers.

Locations. Trials were conducted at Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m); the World Vegetable Center Eastern and Southern Africa Research Station (WorldVeg-ESA), Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long 36.4°E, elevation 1520 m); Chambezi, Pwani region, coastal zone, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); and Malolo, Pwani region, coastal zone, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m). The Thika location, about 50 km northeast from Nairobi, is a trial site of the Simlaw Seed Company. The Arusha region trial was conducted at World-Veg-ESA Research Station and in Ngaramtoni at the Tanzania Agricultural Seed Agency seed multiplication site. The Pwani region (coastal zone) trial was conducted at Chambezi Agricultural Research Station of the Tanzania Agricultural Research Institute (Chambezi hereafter) about 60 km in the northwest of Dar es Salaam city and at the Malolo farmers training center (Malolo hereafter) about 45 km in the northwest of Dar es Salaam city. Figure 1 shows weather data of the four trial locations in Tanzania (WorldVeg-ESA, Ngaramtoni, Chambezi, and Malolo), and Fig. 2 shows the weather data of the Thika location in Kenya. The Arusha region locations are cool environments. The maximum temperature at Thika can reach 30 °C, in spite of its relatively high altitude and low minimum temperature (Fig. 2). The low-altitude coastal zone locations are hotter than the high-altitude tropical locations in the northern zone of Tanzania and the Thika location of Kenya. Each location was considered as a separate environment for data analysis.

Experimental design and field layout. The trial at each location was conducted in a randomized complete block design with three replications. The trials at WorldVeg-ESA and Ngaramtoni were sown on 12 June 2019. Transplanting was done on 10 July 2019 at WorldVeg-ESA and on 16 July 2019 at Ngaramtoni. The trials at both Malolo and Chambezi were sown on 19 July 2019. Transplanting was carried out on 13 and 14 Aug. 2019 at Malolo and Chambezi, respectively. The planting at Thika in Kenya was conducted by direct sowing on 1 Nov. 2019, with seedlings thinned to 30-cm spacing after germination. The trials in Tanzania were conducted during the main amaranth growing season from May to November/December and were irrigated. Drip irrigation was used at WorldVeg-ESA, and furrow irrigation was applied at Ngaramtoni, Chambezi, and Malolo trials. The Thika Kenya trial was conducted under rainfed conditions with supplemental sprinkler irrigation during the short rainy season from October/November to January/February.

Two planting-harvest methods are practiced in vegetable amaranth in Kenya and Tanzania: 1) dense sowing by broadcasting and a single uproot harvest about 21–30 d after sowing and 2) row planting at 25- to 30-cm spacing between plants within rows and 50–60 cm between rows with multiple harvests of leaves and stems during the season. The relatively large spacing between rows is important for furrow irrigation and to fit drip lines. The row planting and repeat harvest method was used in the present study. At all locations, each experimental unit consisted of four rows with 12 plants per row at 30-cm spacing between plants within rows and 60-cm spacing between rows. The

Table 1. Eighteen amaranth lines and two varieties evaluated in participatory variety evaluation in Tanzania and Kenya in 2019–20.

Entry code[z]	Entry[y]	Selection history	Common name(s)	Leaf length width ratio	Leaf vein prominence	Leaf margin	Growth habit	Leaf shape	Leaf blade main color	Seed color
AM1	AVAM1943	UG-AM-27-ES13-4	Spleen amaranth	Small	Strong	Entire	Erect	Ovate	Dark green	Black
AM2	AVAM1604	TZSMN 102-Sel	Prince's feather	Medium	Medium	Sinuate	Prostrate	Lanceolate	Medium green	Yellow
AM3	AVAM1944	AM-25-Sel	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Prostrate	Lanceolate	Medium green	Cream
AM4	AVAM1945	EX-ZAN-ES13-3	None	Medium	Strong	Sinuate	Erect	Lanceolate	Dark green	Black
AM5	AVAM1946	RW-AM-16-ES13-6	Prince's feather	Large	Medium	Sinuate	Prostrate	Ovate	Medium green	Yellow
AM6	AVAM1608	UG-AM-9-ES13-2	Spleen amaranth	Large	Strong	Entire	Erect	Ovate	Dark green	Black
AM7	AbukuAM-6	Abuku amaranth 6	Prince's feather	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Black
AM8	SSCFS-002	SSCFS-002	Purple/red amaranth, bush greens	Large	Strong	Sinuate	Erect	Lanceolate	Medium green	Cream
AM9	AVAM1937	CAMES15-25-1F1-1F2MG-7F3-101F4-441F5-50B1F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Medium green	Yellow
AM10	AVAM1912	CAMES15-25-1F1-1F2MG-1F3-9F4-40F5-10B1F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Light green	Yellow
AM11	AVAM1914	CAMES15-25-1F1-1F2MG-1F3-21F4-98F5-16B1F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Medium green	Yellow
AM12	AVAM1916	CAMES15-25-1F1-1F2MG-1F3-23F4-106F5-17B1F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Medium green	Yellow

(Continued on next page)

Table 1. (*Continued*)

Entry code[z]	Entry[y]	Selection history	Common name(s)	Leaf length width ratio	Leaf vein prominence	Leaf margin	Growth habit	Leaf shape	Leaf blade main color	Seed color
AM13	AVAM1939	CAMES15-25-1F1-1F2MG-7F3-101F4-442F5-51B1F6	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Cream
AM14	AVAM1941	CAMES15-25-1F1-1F2MG-8F3-110F4-485F5-54B1F6	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Yellow
AM15	AVAM1938	CAMES15-25-1F1-1F2MG-7F3-101F4-441F5-50B2F6	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Black
AM16	AVAM1904	CAMES15-25-1F1-1F2MG-1F3-2F4-7F5-3B2F6	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Black
AM17	AVAM1909	CAMES15-25-1F1-1F2MG-1F3-4F4-17F5-7B2F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Medium green	Yellow
AM18	AVAM1932	CAMES15-25-1F1-1F2MG-7F3-90F4-393F5-44B2F6	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Lanceolate	Medium green	Cream
AM19	Madiira 1	Madiira 1 (variety)	Purple/red amaranth, bush greens	Large	Medium	Entire	Erect	Linear	Medium green	Black
AM20	Madiira 2	Madiira 2 (variety)	Purple/red amaranth, bush greens	Medium	Medium	Sinuate	Erect	Lanceolate	Medium green	Black

[z]AM1–AM8 developed by single plant or mass selection from genebank accessions; AM9–AM18 developed by pedigree selection from segregating populations obtained by crossing; AM19 and AM20 are released varieties developed by mass selection from genebank accessions.

[y]All the entries have green stem color and yellow/green inflorescence color; entries were characterized following the International Union for the Protection of New Varieties of Plants (2008) descriptors and/or descriptors used at the World Vegetable Center, Shanhua, Tainan, Taiwan.

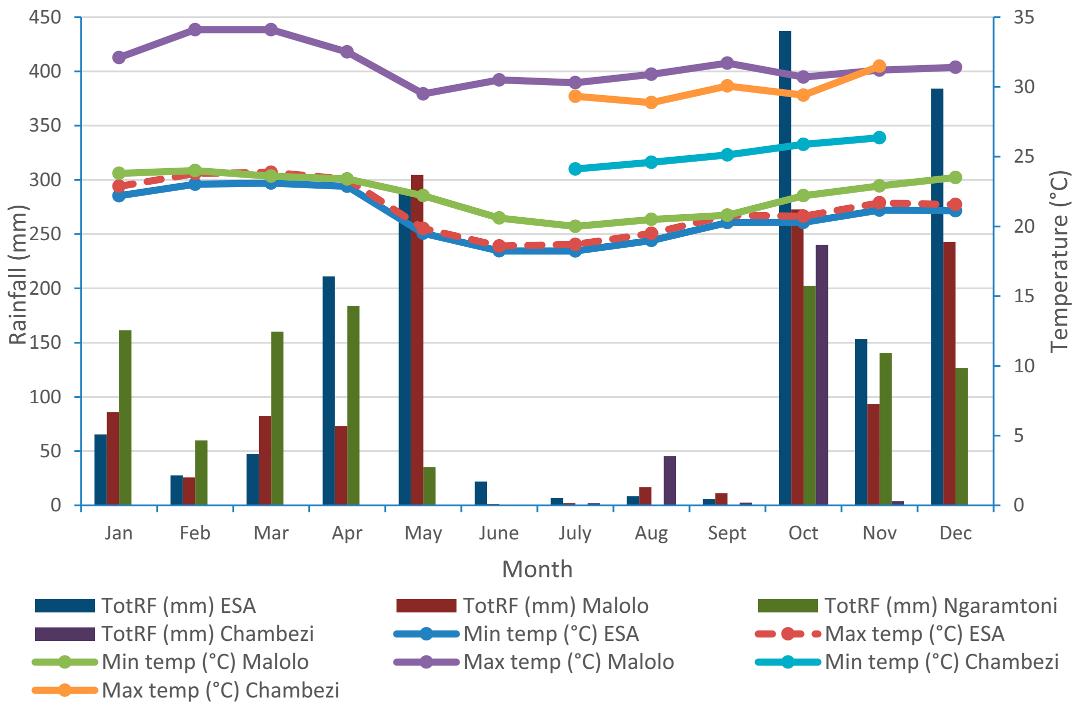

Fig. 1. Total rainfall (TotRF) at World Vegetable Center Eastern and Southern Africa (ESA), Ngaramtoni, Malolo, and Chambezi, Tanzania (January–December) and mean minimum temperature (Min temp) and maximum temperature (Max temp) of ESA, Malolo, and Chambezi (January–December) by month in 2019. Temperature data for Ngaramtoni were not available. Chambezi's temperature data were available only from July to November. The trial was conducted June–Oct. 2019 at ESA and Ngaramtoni and July–Nov. 2019 at Malolo and Chambezi. Location details are as follows: ESA, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long. 36.4°E, elevation 1520 m); Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); and Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); 1 m = 3.3808 ft, 1 mm = 0.0394 inch, (1.8 × °C) + 32 = °F.

central 10 plants per row were harvested from each of the central two rows per plot for marketable vegetable yield determination. All other traits were also measured on the inner plants of the two central rows.

Field management. In the absence of specific fertilizer rates recommendations for each location, the

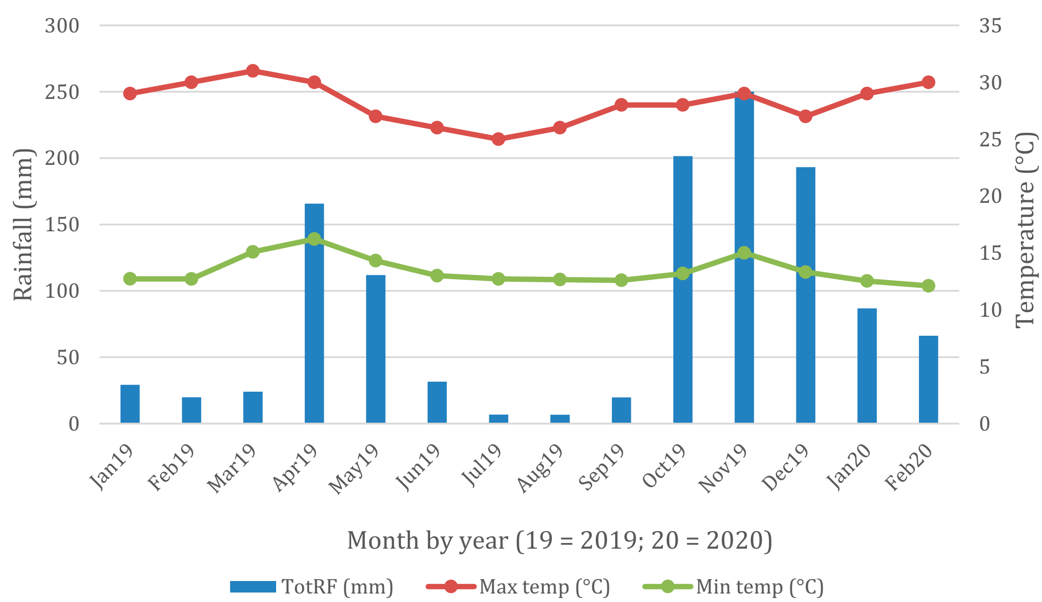

Fig. 2. Total rainfall (TotRF) and mean minimum temperature (Min temp) and maximum temperature (Max temp) at Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m) from Jan. 2019 to Feb. 2020 by month. The trial at this location was conducted Nov. 2019–Feb. 2020; 1 m = 3.3808 ft, 1 mm = 0.0394 inch, (1.8 × °C) + 32 = °F.

rates applied at the WorldVeg-ESA were used. Fertilizer (20N–4.4P–8.3K) was applied manually in all trials as a basal application 1 week after transplanting at the rate of 200 $kg \cdot ha^{-1}$. Urea (46N–0P–0K) was applied as sidedressing 3 weeks after transplanting at the rate of 120 $kg \cdot ha^{-1}$. At Chambezi and Malolo (the coastal zone sandy soil trial locations), decomposed cow dung was applied during plot preparation immediately before transplanting at the rate of 2.75 $kg \cdot m^{-2}$ according to local practice because these soils are low in total soil nitrogen, organic carbon, and clay contents (Dinssa et al., 2019).

Data collection. Data collected on plant height (centimeters), branch number per plant, and leaf length (centimeters) and width (centimeters) during the last marketable vegetable yield harvest were measured on four plants sampled from the central two rows per plot. The leaf sizes were determined on three leaves per sample plant. Plots were harvested multiple times to determine marketable vegetable yields. In Tanzania, each plot was harvested at least four times at about 10- to 15-d intervals. In Kenya, the entries were harvested three times during the growing season. At Thika, plant regrowth after harvests was slow, possibly due to the relatively low night temperatures and dependence on rainfall (Fig. 2). Harvesting was carried out by cutting one-third of the plant height from the top measured on the main stem during the first harvest and branches in subsequent harvests. Sowing to the first harvest took about 55 d averaged over locations, and the time from sowing to the last harvest was about 125 d. Some entries tended to flower between harvests, and flowers were excluded from marketable vegetable yield.

Participatory selection and taste panel. Gender-disaggregated participatory variety selection was conducted at each of the four locations in Tanzania using a 0–4 preference scale, where 0 = very poor and 4 = excellent. In the participatory selection conducted at WorldVeg-ESA, 17 female farmers and 15 male farmers participated, and 22 female and 14 male farmers participated at Ngaramtoni. At Chambezi, 11 female and 19 male farmers participated, and 23 female and seven male farmers participated at Malolo. Before conducting selection in the field plots, focus group discussions with the female and male farmer groups were performed separately to agree on product profiles or traits useful for use as selection criteria in breeding nurseries to identify improved varieties. Each gender focus group first listed important traits for variety selection and then ranked the traits according to their importance. Trait lists and rankings were established after extensive discussions among group members, sometimes involving voting.

A total of 48 WorldVeg staff members (97.9% Tanzanians), including temporary laborers, conducted vegetable amaranth tastings as members of a taste panel to help understand consumer preferences. Each entry was subjected to organoleptic evaluation; plant samples were obtained during the third harvest from pooled harvests of the three replications of the WorldVeg-ESA trial. The plant samples for the organoleptic evaluations were cooked without salt, spices, onion (*Allium cepa*), or oil. Taste was scored independently by each panelist on a scale ranging from 1 to 5, where 1 = very poor, not liked and 5 = excellent, highly liked. The panelists were asked to wash or rinse their mouth between sample tastings.

Statistical analysis. All statistical analyses were conducted using statistical analysis software (GenStat ver. 19.1; VSN International, Hemel Hempstead, UK) except taste scores, in which the percentage of panelists who gave different scores was calculated in spreadsheet software (Microsoft Excel 2016; Microsoft Corp., Redmond, WA). Variance homogeneity and normal distribution tests were run, and no significant deviations from the assumptions required for analysis of variance (ANOVA) were found. Individual location ANOVA and combined ANOVA were conducted using the generalized linear mixed model procedure of GenStat (version 19.1) following a randomized complete block design. Entry (G)-by-location (E) interaction (G × E) analysis was run to estimate the effect of G, E, and their interaction on marketable vegetable yield. Following Yan and Tinker (2006), G and G × E (GGE) biplot analysis was conducted to evaluate and simultaneously display the performances of entry and location graphically. GGE analysis helps identify mega-environments (i.e., locations that share similar environmental conditions) and winner entries in different environments (Yan and Rajcan, 2002).

ANOVA across locations was conducted using the additive main effects and multiplicative interactions (AMMI) analysis to fit the additive main effects of entry and location and to describe the nonadditive multiplicative or the G × E part of the sum of squares by interaction principal component axes (IPCAs) following Zobel et al. (1988). Pearson's correlation analysis was conducted between vegetable yield and plant traits (plant height, branch number per plant, leaf length, and leaf width) and with farmers' selection scores.

Results

Individual ANOVA results indicated significant or highly significant differences among the entries at all locations for marketable vegetable yield, branch number per plant, leaf length, and leaf width (Tables 2 and 3). The differences in plant height were highly significant at WorldVeg-ESA and Ngaramtoni and nonsignificant at Chambezi and Malolo (Table 3). Plant height data were not collected for the Thika trial. Marketable vegetable yields of entries at each location ranged from 12 to 34 $t \cdot ha^{-1}$ at WorldVeg-ESA, from 3 to 43 $t \cdot ha^{-1}$ at Ngaramtoni, from 27 to 60 $t \cdot ha^{-1}$ at Chambezi, from 25 to 55 $t \cdot ha^{-1}$ at Malolo, and from 20 to 46 $t \cdot ha^{-1}$ at Thika (Table 2). Combined ANOVA across locations for marketable vegetable yield indicated highly significant ($P < 0.001$) differences among G, E, and in G × E interaction (Tables 2 and 4). The average yields of entries across locations ranged from 20 to 42 $t \cdot ha^{-1}$, and the average yields of locations across entries ranged from 23 to 45 $t \cdot ha^{-1}$ (Table 2). The two coastal zone trials in Tanzania gave the highest average yields: Chambezi (43 $t \cdot ha^{-1}$) and Malolo (45 $t \cdot ha^{-1}$).

Average plant heights across locations ranged from 47 to 69 cm (Table 3). At individual locations, average heights ranged from 29 to 56 cm (Ngaramtoni), from 44 to 83 cm (WorldVeg-ESA), from 53 to 72 cm (Malolo), and from 55

Table 2. Fresh marketable vegetable yield of 20 amaranth entries evaluated at five locations, and taste panel scores on samples harvested from World Vegetable Center Eastern and Southern Africa trial in 2019.

	Marketable vegetable yield ($t \cdot ha^{-1}$)[z]						Proportion of panelists who gave different taste panel score on the scale of 1–5 (%)[y]		
Entry code	ESA	NGT	CMB	MAL	Thika	Mean	Panelists (no.)	Panelists who scored ≥ 3	Panelists who scored ≥ 4
AM7	12.19	3.23	31.80	31.80	20.87	19.98	46	39.1	23.9
AM3	16.26	10.77	34.30	30.60	19.99	22.38	44	70.5	38.6
AM11	25.22	29.47	50.40	47.00	40.79	38.58	45	73.3	44.4
AM12	28.52	27.54	36.40	41.70	37.13	34.26	48	81.3	45.8
AM16	23.64	28.43	36.50	46.00	33.17	33.55	46	78.3	45.7
AM17	27.69	28.07	47.60	51.80	32.06	37.44	46	63.0	34.8
AM10	22.99	28.33	40.90	44.10	34.86	34.24	47	74.5	40.4
AM9	18.95	29.15	37.60	42.10	28.36	31.23	48	85.4	50.0
AM15	25.01	28.55	47.90	54.60	22.89	35.79	47	76.6	53.2
AM13	27.11	39.79	44.80	53.90	36.87	40.49	46	69.6	52.2
AM18	23.28	22.63	46.00	51.10	20.88	32.78	47	85.1	55.3
AM14	23.87	26.60	47.50	47.90	25.88	34.35	46	73.9	52.2
AM4	25.46	18.72	45.40	55.40	31.01	35.20	46	58.7	26.1
AM19	24.50	29.90	46.70	43.40	30.67	35.03	44	68.2	36.4
AM20	25.78	29.82	60.10	48.60	44.90	41.84	47	55.3	40.4
AM5	16.60	16.73	27.50	24.70	28.02	22.71	48	58.3	33.3
AM8	33.90	43.47	32.40	44.80	46.12	40.14	47	55.3	34.0
AM2	17.28	9.51	27.10	27.20	24.40	21.10	46	80.4	43.5
AM1	26.61	25.40	57.40	51.80	27.71	37.78	46	47.8	26.1
AM6	22.50	24.60	57.70	52.10	27.48	36.88	46	41.3	21.7
Mean	23.37	25.04	42.80	44.50	30.70	33.29	NA	NA	NA
F test (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	NA	NA	NA
$LSD_{0.05}$[x]	7.51	7.36	13.42	12.56	4.244	9.75	NA	NA	NA

[z]ESA = World Vegetable Center Eastern and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); NGT = Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long. 36.4°E, elevation 1520 m); CMB = Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); MAL = Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m); 1 m = 3.2808 ft, 1 $t \cdot ha^{-1}$ = 0.44641 ton/acre.

[y]1 = very poor, not liked by the panelist; 5 = excellent, highly liked by the panelist; NA = not applicable.

[x]Least significant difference at the level of $P < 0.05$ at df for individual location analysis of variance (ANOVA): entry (G) = 19, replication = 2, error (r_e) = 38, and combined ANOVA: G = 19, location (E) = 4, replication within location = 10, G × E interaction = 76, r_e = 190.

Table 3. Plant height, branch number per plant, leaf length, and leaf width of 20 amaranth entries measured at the final marketable vegetable yield harvest in trials conducted at four location in Tanzania and one location in Kenya in 2019.

Entry code	Plant ht (cm)[z]					Branches (no./plant)						Leaf length (cm)						Leaf width (cm)					
	ESA	NGT	CMB	MAL	Mean	ESA	NGT	CMB	MAL	Thika	Mean	ESA	NGT	CMB	MAL	Thika	Mean	ESA	NGT	CMB	MAL	Thika	Mean
AM7	52.3	32.8	66.0	55.3	51.6	11.5	4.9	28.3	31.6	9.3	17.1	8.1	7.5	6.9	6.2	13.5	8.4	4.3	3.6	3.2	3.0	4.6	3.7
AM3	54.3	38.0	61.9	53.3	51.9	11.3	7.1	34.3	48.9	9.7	22.3	8.8	10.0	6.8	6.7	17.8	10.0	4.1	4.5	3.1	3.3	4.8	4.0
AM11	74.1	52.1	69.1	62.8	64.5	13.0	16.7	34.5	44.5	15.0	24.7	11.3	12.6	8.1	9.2	17.2	11.7	3.7	4.1	3.4	3.6	5.3	4.0
AM12	71.7	44.6	64.5	59.7	60.1	16.9	15.3	37.2	36.7	15.3	24.3	11.9	12.8	8.3	8.6	18.1	11.9	4.2	4.5	3.1	3.2	4.7	3.9
AM16	69.6	48.0	68.2	64.8	62.7	15.8	13.2	30.5	40.3	14.3	22.8	10.0	10.9	8.5	9.4	16.8	11.1	4.6	4.7	4.0	4.4	5.1	4.5
AM17	82.7	51.5	71.9	70.7	69.2	15.8	12.4	33.7	39.5	14.7	23.2	11.6	13.0	8.6	10.1	14.2	11.5	3.4	4.1	3.4	3.7	3.6	3.6
AM10	62.5	42.3	59.9	63.1	57.0	14.5	9.2	26.3	52.7	15.3	23.6	11.9	11.1	8.0	9.1	16.7	11.4	3.9	3.3	3.4	2.9	5.1	3.7
AM9	63.4	48.3	65.1	71.8	62.2	15.4	16.1	27.8	36.8	16.7	22.6	10.7	10.4	8.8	10.9	17.0	11.6	3.9	3.8	3.7	4.5	4.1	4.0
AM15	80.7	44.9	66.5	67.2	64.8	17.2	12.8	32.5	54.9	14.7	26.4	10.1	9.8	8.0	8.9	14.8	10.3	3.6	3.8	3.2	3.2	4.4	3.6
AM13	74.3	36.1	60.3	64.4	58.8	17.1	11.7	29.3	53.4	13.3	25.0	10.6	9.2	7.9	7.9	14.2	10.0	3.7	3.2	3.1	3.3	4.7	3.6
AM18	66.6	48.0	83.1	67.9	66.4	15.6	17.6	35.1	52.1	14.0	26.9	10.7	10.5	8.8	10.7	14.2	11.0	3.4	3.1	3.4	4.3	3.9	3.6
AM14	62.3	46.3	71.0	61.7	60.3	14.3	16.1	30.8	48.0	14.0	24.6	9.9	9.6	8.9	9.0	14.0	10.3	3.8	3.7	3.8	3.4	4.4	3.8
AM4	44.3	28.8	59.4	53.8	46.6	8.3	15.1	35.9	31.8	13.7	21.0	12.6	9.7	8.5	8.5	13.8	10.6	6.3	4.6	4.4	4.0	5.3	4.9
AM19	62.7	56.1	65.9	65.8	62.6	19.7	25.5	34.3	31.0	12.7	24.6	11.4	12.1	10	9.5	12.6	11.1	2.2	2.6	2.5	2.2	2.9	2.5
AM20	78.5	47.3	73.1	60.1	64.8	13.9	13.3	37.6	38.3	18.7	24.4	10.4	10.6	8.2	7.4	16.2	10.6	4.9	5.0	3.9	3.6	5.3	4.5
AM5	58.2	39.0	58.3	57.4	53.2	13.0	12.8	43.1	38.6	9.0	23.3	9.3	10.1	6.5	6.5	15.1	9.5	5.0	5.5	3.2	3.3	5.3	4.4
AM8	67.0	51.7	57.2	53.7	57.4	13.9	11.6	28.8	33.0	16.7	20.8	10.9	10.7	6.0	6.3	14.7	9.7	5.6	5.3	2.9	2.9	5.2	4.4
AM2	57.3	38.0	55.1	56.3	51.7	11.7	14.6	44.8	41.1	8.7	24.2	9.8	9.1	6.0	6.6	15.2	9.3	4.9	5.0	2.9	3.4	4.9	4.2
AM1	57.9	41.3	68.6	65.9	58.4	14.7	14.9	27.2	40.7	12.0	21.9	9.2	10.9	8.2	7.5	13.7	9.9	5.6	6.8	5.9	4.8	5.5	5.7
AM6	55.7	37.6	71.9	67.8	58.3	13.0	12.0	25.7	38.4	12.7	20.4	10.4	10.7	8.7	7.8	13.6	10.2	6.4	7.0	6.0	4.9	5.3	5.9
Mean	64.8	43.6	65.9	62.2	59.1	14.3	13.6	32.9	41.6	13.5	23.2	10.5	10.6	8.0	8.3	15.2	10.5	4.4	4.4	3.6	3.6	4.7	4.1
F test (*P*)	0.001	0.003	0.063	0.121		0.002	0.015	0.014	0.003	0.001		0.002	0.032	0.001	0.001	0.038		0.001	0.001	0.001	0.001	0.001	
$LSD_{0.05}$[y]	14.1	12.2	NS	NS		4.3	8	9.9	13.1	3		1.9	2.7	1.6	1.2	3.3		1.0	1	0.8	0.7	0.8	

[z]ESA = World Vegetable Center Easter and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); NGT = Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long. 36.4°E, elevation 1520 m); CMB = Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); MAL = Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m); 1 m = 3.3808 ft, 1 cm = 0.3937 inch.

[y]Least significant difference at the level of $P < 5\%$ at df for individual location analysis of variance: entry = 19, replication = 2, error = 38. NS = differences among entries in the same column nonsignificant.

to 83 cm (Chambezi). AM17 and AM4 had the tallest and shortest plant heights, respectively. The average branch number per plant across locations ranged from 17 to 27 cm, with AM18 and AM7 producing the highest and lowest branch number per plant, respectively. AM7 had the shortest leaf length, whereas AM12 had the longest leaf length across locations. AM6 and AM19 produced the widest and narrowest leaves, respectively.

In the combined ANOVA for marketable vegetable yield, E explained the highest proportion (53.7%) of the treatment sum of squares (Table 4). G explained the second highest proportion of the treatment sum of squares (28.5%), followed by G × E (17.8%). AMMI analysis of the marketable vegetable yield partitioned the G × E sum of squares into two highly significant IPCAs (Table 4). The two IPCAs (IPCA1 and IPCA2) together explained 85.2% of the G × E sum of squares. IPCA1 and IPCA2 accounted for 64.0% and 21.2% of the interaction sum of squares, respectively. Table 5 lists the first four entries with the highest values for plant height, branch number per plant, leaf length, leaf width, and marketable vegetable yield per location. Most of the top four highest-yielding entries in one location were also among the best yielding entries in one or more other locations. AM13, AM20, and AM8 were among the top four highest-yielding entries in three of the five locations. AM8 was the highest-yielding entry in the two relatively high-altitude locations of Tanzania and the Kenya location, whereas AM6 and AM1 were the highest-yielding entries in the two coastal locations in Tanzania. AM13 produced yields above the mean at low-altitude and high-altitude locations. AM17 was among the four tallest at all locations where plant heights were measured. Moreover, AM17 was among the four best entries for leaf length in four of the five locations. AM19 was also among the best four entries with long leaf length in four of the five locations. AM17 and AM19 were not among the highest for leaf width at any of the locations.

The GGE biplot analysis on marketable vegetable yield grouped the five locations into two mega-environments (MEs) (Fig. 3). The two coastal zone locations of Tanzania clustered closely and could be grouped into one ME (ME1 here-

Table 4. Additive main effect and multiplicative interaction analysis of variance on vegetable yield of 20 amaranth entries in Kenya and Tanzania in 2019.

Source[z]	df	Sum of squares	Mean squares	F-test	*P*	Proportion of sum of squares (%)[y]
Treatment	99	43,584	440.2	12.89	<0.001	100.0
Entry (G)	19	12,420	653.7	19.14	<0.001	28.5
Location (E)	4	23,402	5,850.5	57.21	<0.001	53.7
Replication within E	10	1,023	102.3	2.99	0.002	–
G × E	76	7,763	102.1	2.99	<0.001	17.8
IPCA1	22	4,966	225.7	6.61	<0.001	64.0
IPCA2	20	1,646	82.3	2.41	0.001	21.2
Residual	34	1,151	33.9	0.99	0.489	14.8
Error	190	6,490	34.2			
Total	299	51,097	170.9			

[z]IPCA1 = interaction principal component axis one; IPCA2 = interaction principal component axis two.

[y]The proportions of the sum of squares (SS) of G, E, and G × E interaction SS were calculated from treatment SS; the proportions of SS of IPCA1, IPCA2, and residuals SS were calculated from G × E interaction SS.

after). The two locations in northern Tanzania and the Kenya location formed another ME (ME2 hereafter). Differences among locations in altitude, weather conditions (Figs. 1 and 2), and soil characteristics (very sandy soil in the coastal locations vs. loamy, volcanic, and clay soil in the other locations) affected entry performance

Table 5. Four best amaranth entries for vegetable yield and other traits selected in each location by the additive main effect and multiplicative interaction analysis based on two significant interaction principal component axes measured on 20 entries grown in five locations in Kenya and Tanzania in 2019–20.

Plant ht (cm)[z]		Branch (no./plant)		Leaf length (cm)		Leaf width (cm)		Yield ($t \cdot ha^{-1}$)[x]	
Entry code[y]	Mean	Entry code	Mean	Entry code	Mean	Entry code	Mean	Entry code	Mean
ESA	64.8	ESA	14.3	ESA	10.5	ESA	4.4	ESA	23.4
AM17	82.7	AM19	18.2	AM17	12.2	AM6	6.2	AM8	33.8
AM15	80.9	AM18	16.9	AM12	12.0	AM1	5.9	AM20	32.0
AM20	78.0	AM15	16.6	AM19	12.0	AM8	5.5	AM13	30.8
AM13	74.7	AM9	16.2	AM11	11.7	AM4	5.4	AM11	29.2
Ngramtoni	43.6	Ngaramtoni	13.6	Ngaramtoni	10.6	Ngaramtoni	4.4	Ngaramtoni	25.0
AM19	56.3	AM19	21.1	AM12	12.7	AM6	7.2	AM8	43.4
AM11	51.7	AM12	16.9	AM17	12.3	AM1	6.7	AM13	38.4
AM17	51.6	AM20	16.1	AM11	12.2	AM4	5.3	AM16	29.6
AM8	51.3	AM9	15.9	AM19	11.7	AM8	5.3	AM12	29.1
Chambezi	65.9	Chambezi	32.9	Chambezi	8.0	Chambezi	3.6	Chambezi	42.8
AM18	79.5	AM2	45.1	AM19	9.6	AM6	5.8	AM20	57.9
AM6	73.3	AM5	43.1	AM18	9.5	AM1	5.7	AM1	56.3
AM17	72.4	AM12	36.9	AM9	9.4	AM16	4.2	AM6	56.3
AM1	69.9	AM20	36.9	AM17	9.3	AM4	4.1	AM4	49.8
Malolo	62.2	Malolo	41.6	Malolo	8.3	Malolo	3.6	Malolo	44.5
AM18	72.9	AM15	54.9	AM9	10.4	AM1	5.0	AM15	54.9
AM17	70.0	AM13	53.5	AM18	10.1	AM6	5.0	AM13	53.8
AM20	66.0	AM10	52.9	AM19	9.6	AM16	4.3	AM1	53.8
AM6	65.8	AM18	51.4	AM17	9.3	AM9	4.1	AM6	53.4
–[w]	–	Thika	13.5	Thika	15.2	Thika	4.7	Thika	30.7
–	–	AM19	18.3	AM12	18.1	AM4	5.7	AM8	46.2
–	–	AM9	16.1	AM3	17.8	AM6	5.3	AM20	43.2
–	–	AM18	15.8	AM11	17.3	AM8	5.3	AM11	39.4
–	–	AM15	15.4	AM9	17.1	AM1	5.3	AM12	37.6

[z]1 cm = 0.3937 inch.

[y]ESA = World Vegetable Center Easter and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long 36.4°E, elevation 1520 m); Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m); 1 m = 3.3808 ft.

[x]1 $t \cdot ha^{-1}$ = 0.4464 ton/acre.

[w]Data not available for Thika location.

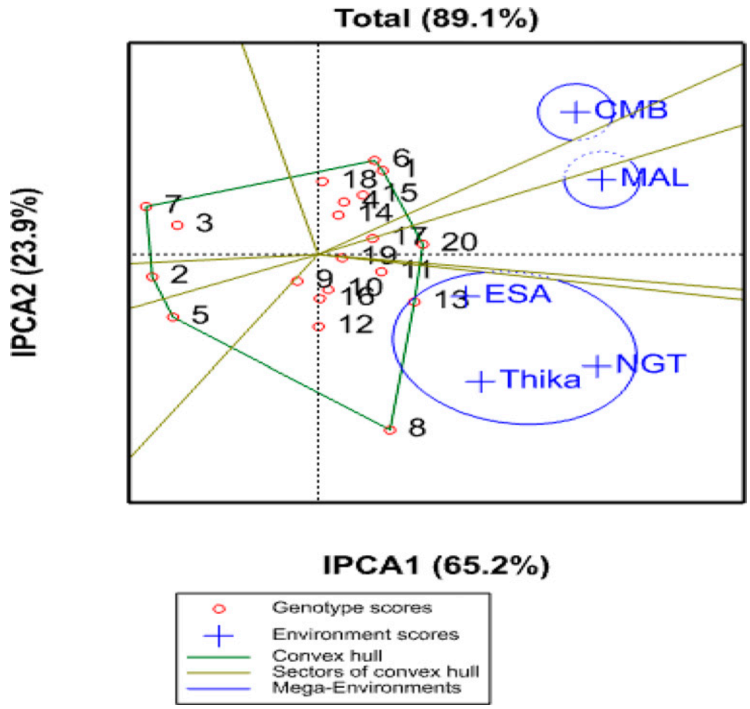

Fig. 3. Entry (G) and G-by-location (E) interaction (GGE) biplot of marketable vegetable yield measured on 20 amaranth entries in Kenya and Tanzania, 2019. Blue font with the plus (+) sign stands for location [ESA = World Vegetable Center Eastern and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); NGT = Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long 36.4°E, elevation 1520 m); CMB = Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); MAL = Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); Thika, Kiambu county, Kenya (lat. 01°S, long. 37°E, elevation 1548 m)]. Red circle dots labeled by numbers are entry code given in Table 1 with "AM" dropped in this figure; see Table 1 for the corresponding entry names and selection history; 1 m = 3.3808 ft.

and contributed to the highly significant differences in marketable vegetable yields among locations as indicated by the AMMI analysis. In the GGE biplot analysis, the two ME1 locations (Chambezi and Malolo) and Ngaramtoni from ME2 were located further from the GGE biplot origin, whereas WorldVeg-ESA in ME2 was mapped closer to the origin (Fig. 3). Locations mapped far from the GGE biplot origin made large contributions to G × E. Similarly, entries located distantly from the biplot origin made large contributions to G × E, whereas those near the origin of the biplot tended to be stable across environments and contribute less to G × E. Entry code 8 (AM8 in Table 1), one of the entries further from the GGE biplot origin (Fig. 3), performed the best for yield in three locations: WorldVeg-ESA, Ngaramtoni, and Thika (Tables 2 and 5). Four entries (AM7, AM2, AM3, and AM5) with strong negative loadings on IPCA1 had a poor performance in all locations. The two spleen amaranth entries and all but two purple/red amaranth or bush greens entries were mapped on the positive axis of the IPCA1, with eight entries on the IPCA2-positive axis and seven entries on the IPCA2-negative axis. The two spleen amaranth entries (AM1 and AM6) mapped on the positive axis of IPCA2 (Fig. 3) appear to be not the best performers in the relatively high-altitude locations (i.e., WorldVeg-ESA, Ngaramtoni, and Thika) (Tables 2 and 5). 'Madiira 1' (entry code AM19) was the most stable but was low yielding in most of the locations, and 'Madiira 2' (entry code AM20) was among the high-yielding entries in almost all locations.

Participatory selection and taste panel. Traits identified by farmers during participatory selection and applied in the entry evaluations conducted by the farmers in the field trials are given in Table 6. Nine traits were identified independently by female and male farmer participants. Trait rankings of the gender groups matched for some traits but differed for others. Marketability, capacity for multiple harvests, and tolerance to diseases and insects were unanimously ranked as the second, fourth, and fifth most important traits by both gender groups. However, rapid regrowth or biomass accumulation and recovery from repeat harvests were ranked first by the female farmer group and third by the male farmers group; drought tolerance was ranked first by male farmers but sixth by female farmers. Moreover, the female farmers ranked dark green leaf color as the third most important trait, whereas this trait ranked sixth among male farmers. Both gender groups ranked broad leaves as the seventh, nutrient content as the eighth, and non-dark seed color as the ninth most important traits. Both female and male farmer groups identified entries AM6 and AM1 as their preferred varieties to grow on their farms (Table 7). AM7, AM3, AM5, and AM2, which had strong negative loadings on IPCA1 (Fig. 3), were the least liked entries by both female and male farmers and were among the lowest-yielding entries in all locations (Table 2). AMMI analysis identified the best four entries selected by female and male farmer groups per location (Table 8). Entries AM6 and AM1 were among the best four entries selected by both female

Table 6. Amaranth priority traits identified and ranked according to their importance by female and male farmers as selection criteria in breeding nurseries. Note that many of the traits for selection are interrelated.

Serial no.	Priority traits for selection	Rank[z]
1	Fast growing varieties (early biomass accumulators) and quick recovering from repeat cuttings (refers to the time lapse between one harvest and the other)	1, 3
2	Marketability, expressed in terms of leaf color, cooking quality (= not getting too soft) and taste quality/preferably local type leaf color and taste but with high yield	2, 2
3	Dark green color leaf (an indication of good taste and nutrient content for farmers)	3, 6
4	Ability to be harvested several times from the same planting (refers to the number of harvests per a growing season; about 4–5 times harvest but depends on variety and moisture availability)	4, 4
5	Tolerant to diseases and insects (such as seedling stage wilt, foliar insects)	5, 5
6	Tolerant to drought (varieties that grow with less frequent irrigation and amount of water); farmers face intermittent moisture shortage or drought in rainfed production, and irrigation water is not always available to a farmer; there is a rationing system among many farmers) that irrigation time interval could be long	6, 1
7	Broad leaves (if it combines with deep green leaf)	7, 7
8	High nutrients content (expressed in terms of deep green leaf color)	8, 8
9	White seed color for use as grain for farmers interested in grain as well	9, 9

[z]Female farmers group and male farmers group rank, respectively.

farmer and male farmer groups in three of the four locations.

Taste panel members did not agree on a single best tasting entry, but most preferred AM18, AM15, AM13, and AM14 (Table 2); the panelists said these entries have good mouth feel and are not too soft, too hard, or too fibrous. The highest percentage of panelists (55%) scored AM18 as 4 or 5 (on a 1–5 scale, where 5 = best) (Table 2). Moreover, these four entries were among the entries that recorded high female and male farmer selection scores in participatory selection conducted under field conditions at the four locations in Tanzania (Table 6). The same four entries were also among the high-yielding entries, indicating that they combined high yields with consumer and farmer preferences.

Marketable vegetable yield was positively correlated with leaf length at Worldveg-ESA (r = 0.63**), Ngaramtoni (r = 0.48*), Chambezi (r = 0.65**), and Malolo (r = 0.52*) and with plant height at Worldveg-ESA (r = 0.52*), Ngaramtoni (r = 0.58**), Chambezi (r = 0.63**), and Malolo (r = 0.53*) (*significant at $0.01 < P \leq 0.05$, **significant at $P \leq 0.01$; df = 18). At Thika in Kenya, the correlation of marketable vegetable yield with leaf length and leaf width were nonsignificant, but the correlation with branch number per plant was significant. Marketable vegetable yield was positively correlated with female farmer selection scores at all the four locations: WorldVeg-ESA (r = 0.44**), Ngaramtoni (r = 0.53*), Chambezi (r = 0.68**), and Malolo (r = 0.61**). The correlation between marketable vegetable yield and male farmer selection scores was highly significant at Ngaramtoni (r = 0.63**), Chambezi (r = 0.87**), and Malolo (r = 0.68**). Female and male farmer selection scores were highly correlated at all the four locations where farmers' selection was conducted: WorldVeg-ESA (r = 0.91**), Ngaramtoni (r = 0.97**), Chambezi (r = 0.89**), and Malolo (r = 0.80**).

Discussion

The study evaluated the performance of amaranth entries for marketable vegetable yield and other key traits as well as farmer and consumer preferences at different locations in Tanzania and Kenya. The study was conducted following a gender-disaggregated farmer participatory approach, and a taste panel was conducted to assess consumer preferences. The study locations differed in altitude and weather conditions (Figs. 1 and 2) and soil characteristics. Combined ANOVA results of marketable vegetable yield revealed that location followed by entry described the highest proportion of the sum of squares of treatment in agreement with previous amaranth studies (Dinssa et al., 2019) and in rice [*Oryza sativa* (Kulsum et al., 2012)]. In agreement with Dinssa et al. (2019), trials in the two coastal locations in Tanzania (Chambezi and Malolo), characterized by low altitude, high temperatures, and sandy soil, showed higher average yields than the trials in northern Tanzania and Kenya characterized by higher altitudes; lower temperatures; and loamy, volcanic soils. In Japan, Khandaker et al. (2009) found that mean air temperatures of 28 to 29 °C increased Chinese Spinach (*Amaranthus tricolor*) biomass yields compared with lower mean air temperatures (18 to 19 °C). Dinssa et al. (2019) reported that low-altitude and high-temperature locations gave higher marketable vegetable amaranth yields regardless of season. Previous studies have shown that amaranth can tolerate abiotic stresses such as drought and salinity by reducing osmotic stress (Sarker and Oba, 2020d; Sarker et al., 2018b), reactive oxygen species (Sarker and Oba, 2018a), and oxidative damage (Sarker and Oba,

Table 7. Gender-disaggregated farmers' selection scores at four locations in Tanzania in 2019.

Entry code	Female farmers selection score (0–4 scale)[z] ESA (n = 17)	NGT (n = 22)	CMB (n = 11)	MAL (n = 23)	Mean	Male farmers selection score (0–4 scale) ESA (n = 15)	NGT (n = 14)	CMB (n = 19)	MAL (n = 7)	Mean
AM7	1.7	0.8	0.6	0.8	1.0	1.7	1.0	0.7	1.1	1.1
AM3	1.8	0.8	0.6	2.0	1.3	1.9	1.1	1.2	1.2	1.4
AM11	2.0	1.5	2.9	2.3	2.2	1.8	1.8	2.9	2.8	2.3
AM12	2.4	1.9	2.4	2.5	2.3	2.5	2.1	2.1	2.7	2.3
AM16	2.3	2.3	2.3	2.6	2.4	2.1	2.2	2.4	2.7	2.3
AM17	2.3	2.0	2.7	3.1	2.5	2.3	2.2	2.8	3.1	2.6
AM10	2.0	2.0	2.5	2.5	2.2	1.6	2.2	2.1	2.9	2.2
AM9	2.1	1.6	2.3	2.9	2.2	1.7	1.9	2.4	3.0	2.2
AM15	1.9	1.6	2.3	2.2	2.0	1.8	1.9	2.5	2.8	2.3
AM13	2.0	1.7	2.6	2.1	2.1	1.8	1.8	2.5	1.9	2.0
AM18	2.0	2.0	2.8	3.0	2.4	2.0	1.9	2.7	3.4	2.5
AM14	1.7	1.6	2.8	2.4	2.1	1.9	1.8	3.1	3.0	2.4
AM4	2.3	2.1	2.5	2.0	2.2	2.1	2.0	2.8	3.0	2.5
AM19	2.6	2.3	2.4	2.5	2.5	2.2	2.3	2.2	2.8	2.3
AM20	2.8	2.7	2.4	2.1	2.5	2.9	2.9	2.9	2.1	2.7
AM5	2.1	1.2	0.8	1.4	1.4	2.3	1.6	0.9	1.1	1.5
AM8	2.6	2.8	1.8	1.3	2.1	2.8	2.7	1.4	1.1	2.0
AM2	2.3	1.1	0.8	1.4	1.4	2.3	1.3	1.1	1.7	1.6
AM1	3.0	3.5	2.1	3.1	2.9	3.1	3.1	3.0	2.3	2.9
AM6	3.1	3.5	2.3	3.3	3.0	3.1	2.9	3.0	2.9	3.0
Mean	2.3	1.9	2.1	2.3	2.1	2.2	2.0	2.2	2.4	2.2
F test (P)	<0.001	<0.001	<0.001	<0.001	–	<0.001	<0.001	<0.001	<0.001	–
$LSD_{0.05}$[y]	0.3	0.5	0.5	0.7	–	0.5	0.5	0.7	0.9	–

[z]ESA = World Vegetable Center Easter and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); NGT = Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long. 36.4°E, elevation 1520 m); CMB = Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); MAL = Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); 1 m = 3.23808 ft; n = number of farmers; 0 = very poor, 4 = excellent.

[y]Least significant difference at the level of $P < 5\%$ at df for individual location analysis of variance: entry = 19, replication = 2, error = 38.

2018b) in plant cells. The current and previous results indicated that amaranth can yield well under high temperatures and could be better adapted to global warming than many other crops. However, there must be sufficient soil moisture to compensate for higher evapotranspiration losses under high temperatures. High temperatures accompanied by drought can adversely affect yield components such as plant height and leaf sizes (personal observation in field trials and in volunteer plants growing in farm edges or road sides). For example, a typical amaranth variety that grows about 2 m tall in Arusha, Tanzania (about 26 °C maximum temperature) with sufficient soil moisture grows less than 1 m in Bamako, Mali, where maximum temperatures can reach 35 °C with sparse rainfall. Under high temperatures in the dry season, amaranth plants usually develop a longer tap root; Dinssa et al. (2019) reported that the root lengths of high-yielding entries were greater than the root lengths of low-yielding entries in the hot-dry season. A review paper by Comas et al. (2013) on traits for drought tolerance in crops reported that long root growth ability of a crop plant is among the characteristics contributing to drought tolerance and better yield performance under low moisture conditions.

The correlation of vegetable yield with leaf length in the current study is in agreement with a previous study in vegetable amaranth (Dinssa et al., 2019; Sarker et al., 2014, 2015b). In the current study, yield was positively correlated with plant height in the four Tanzanian locations, which corroborates previous findings of vegetable amaranth (Dinssa et al., 2019; Sarker et al., 2016). Dinssa et al. (2019) reported that vegetable yield was significantly correlated with branch number per plant in three locations in trials conducted at five locations in wet-cool and hot-dry seasons. In the current study, yield and branch number per plant were significantly correlated only at Thika, Kenya. The different results between the two studies might be explained by differences in entries used and/or environmental conditions. The lack of correlation between marketable vegetable yield and leaf width in the present study as opposed to the positive correlation result in Dinssa et al. (2019) could be due to differences in the types and numbers of amaranth species evaluated in the two studies. About 35% of the entries used in Dinssa et al. (2019) were spleen amaranth, which have broader leaves than other amaranth species, whereas spleen amaranth entries constituted only 10% of the entries evaluated in the present study. A positive correlation between marketable vegetable yield and each of leaf width, leaf length, and plant height and a negative correlation between yield and branch number were reported by Tejaswini et al. (2017).

Farmer participatory selection is a critical part of varietal selection of African traditional vegetables, especially because little information is available about farmer and market preferences. WorldVeg applies farmer participatory selection to identify priority traits for leafy and fruit type African traditional vegetables for use in breeding. In the current study, farmer participatory selection identified and ranked nine key amaranth traits. The first six most essential traits identified by both or either female or male

Table 8. The four best amaranth entries selected by each female farmer group and male farmer group per location as identified by the additive main effect and multiplicative interaction analysis based on two significant interaction principal component axes measured on 20 entries grown in four locations in Tanzania in 2019.

Female farmers selection		Male farmers selection		Avg of female and male farmers selection	
Entry[z]	Score (0–4 scale)[y]	Entry	Score (0–4 scale)	Entry	Score (0–4 scale)
ESA	2.2	ESA	2.2	ESA	2.2
AM1	3.5	AM1	3.1	AM6	3.2
AM6	3.5	AM6	3.1	AM1	3.2
AM20	2.8	AM8	2.9	AM20	2.7
AM8	2.6	AM20	2.9	AM8	2.7
Ngaramtoni	1.9	Ngaramtoni	2.0	Ngaramtoni	2.0
AM1	3.1	AM1	3.1	AM1	3.1
AM6	3.1	AM6	2.9	AM6	3.0
AM8	2.8	AM20	2.9	AM20	2.9
AM20	2.8	AM8	2.4	AM8	2.7
Chambezi	2.1	Chambezi	2.4	Chambezi	2.2
AM18	2.8	AM1	3.4	AM14	2.8
AM14	2.8	AM14	3.1	AM6	2.8
AM11	2.8	AM6	3.0	AM18	2.8
AM17	2.7	AM20	3.0	AM17	2.8
Malolo	2.3	Malolo	2.2	Malolo	2.3
AM17	3.1	AM18	3.0	AM18	3.1
AM6	3.0	AM17	3.0	AM17	3.1
AM18	2.9	AM14	3.0	AM6	2.9
AM1	2.9	AM4	2.9	AM9	2.8

[z]ESA = World Vegetable Center Easter and Southern Africa, Arusha region, Tanzania (lat. 3.4°S, long. 36.8°E, elevation 1235 m); Ngaramtoni, Arusha region, Tanzania (lat. 3.2°S, long 36.4°E, elevation 1520 m); Chambezi, Pwani region, Tanzania (lat. 6.2°S, long. 38.5°E, elevation 39 m); Malolo, Pwani region, Tanzania (lat. 6.7°S, long. 39.1°E, elevation 358 m); 1 m = 3.3808 ft.

[y]0 = very poor, 4 = excellent.

farmers included 1) fast-growing or biomass accumulating entries and quick recovery from repeat cutting, 2) drought tolerance, 3) marketability, 4) dark green leaf color, 5) ability to be harvested several times from the same plants, and 6) disease and insect pest tolerances. This result is in agreement with findings by Dinssa et al. (2020) and Adeniji and Aloyce (2013), who identified most of the traits found in the current study. Here we compared groups of female and male farmers in the ranking of key traits to select amaranth varieties. For both gender groups, high and positive correlations were found between selection scores and marketable vegetable yield in almost all locations. The high positive correlations between female and male farmer selection scores at all the locations suggest that male and female farmers shared similar trait preferences for amaranth varieties. Farmers in both gender groups in this study produced amaranth for local or regional markets and for home consumption, and female and male farmers ranked marketability, capacity for multiple harvests, and disease/insect resistance as important variety traits. Varieties that can be harvested multiple times allow farmers to sell produce over a longer period, possibly even out price fluctuations, and enjoy continuous supplies for home consumption from the same crop. Marketability is critical because vegetable yield is highly perishable and must be sold quickly. Although gender differences in trait ranking and amaranth variety selection were minor in this study, inclusion of different farmers might have led to different results. Consequently, participatory variety selection should include the opinions of male and female farmers.

Surveys among rice-producing farmers in India reported gender differences in trait preferences and variety selection (Mehar et al., 2017). Tegbaru et al. (2020) identified gender-shared and distinct varietal traits in maize. In the present study, drought tolerance was ranked higher by men (first) compared with women (sixth). The difference may indicate greater male involvement in amaranth irrigation. It is possible that when water supplies are limited, male farmers may prefer to irrigate other crops instead of amaranth. Drought tolerance is an especially important trait for hot-dry environments, and amaranth varieties that could yield relatively well under drought may open up possibilities for off-season production. Drought-tolerant varieties could be better adapted for off-season production in hot-dry environments when market prices would be higher.

Farmers often associate dark-green leaf color with high nutrient content (Keding et al., 2021), a trait that was more valued by the female farmers in the present study. The relationship between the degree of greenness and nutrient content has been not studied. Dinssa et al. (2020) reported high zinc and sodium contents in spleen amaranth entries that visually appear more dark-green than purple/red amaranth or bush greens and prince's feather entries in their study. Most amaranth entries identified as deep green color belong to spleen amaranth.

The clustering of the northern Tanzania locations and the location in Kenya indicates that initial selection could be done at the WorldVeg-ESA research station in Arusha, Tanzania, and advanced yield trials targeting release in Kenya could be conducted at Thika. Depending on availability of resources, amaranth varieties for coastal areas of Tanzania may require a different breeding approach. Dinssa et al. (2019) described the northern cool environment and the hot coastal environment of Tanzania as two different MEs and suggested independent selection environments for each ME.

Three of the four amaranth entries (entry codes AM2, AM3, AM5, and AM7) that separated themselves on the IPCA1 negative axis were prince's feather species; AM3 is purple/red amaranth or bush greens. The common characteristic of the four entries is their earliness in flowering as compared with the other entries in the study. The leaves of prince's feather entries tended to be softer compared with most other entries. The separation of the entries in the study into the two axes of IPCA2 could be caused by differences in their adaptation to environmental conditions (e.g., temperature). This seems clear because AM6 and AM1 performed well in the high-temperature coastal locations, whereas AM8 performed well in the high-altitude and cool-temperature locations. The loading of all the locations on the same positive axes of IPCA2 could be due to some similarity among the locations, although they differ in many environmental conditions (e.g., temperature and soil conditions).

Making more varieties available in the farming system helps maintain diversity and sustainable crop production, buffering the effects of biotic and abiotic stresses that frequently arise due to climate change. The current study identified five promising advanced lines and retained for distinctiveness, uniformity, and stability (DUS) tests and possible release as commercial varieties. AM8 and AM12 were retained for DUS testing and possible release in central Kenya, and AM15, AM13, and AM14 were retained for DUS testing and possible release in Tanzania. The above lines combine high consumer acceptance with their high yields. Moreover, AM13 and AM8 produce white, cream-colored seeds, and AM12 and AM14 have yellow seeds; both colors are preferred by East African grain amaranth consumers. The commercial varieties AM19 and AM20 are registered in Tanzania and Kenya, but both are late flowering and produce low seed yields (Dinssa et al., 2018). AM19 and AM20 were varieties selected for their high vegetative yields without considering their seed yields, which is important for economical seed production by seed companies and seed enterprises. Low seed yields increase variety seed production costs, ultimately increasing seed cost to farmers. High seed yields are important to seed producers, and the candidate lines yield at least 18% more seed per hectare than AM19 and AM20.

Conclusions

Twenty amaranth entries were evaluated for vegetable yield, agronomic traits, and organoleptic taste tests in replicated, farmer-participatory selection trials at one location in Kenya and at four locations in Tanzania. Female and male farmers independently identified nine important amaranth variety traits, and trait rankings by each gender were similar, with only slight differences. In organoleptic taste evaluations, taste panelists did not agree on a single entry, but entries receiving high average scores were identified. The five trial locations clustered into two mega-environments: highland locations with relatively cool temperatures and lowland coastal locations with higher temperatures. The study identified lines for DUS testing and possible release as commercial varieties in each country. The lines have been selected for combining high yields with consumer and farmer preferences. The lines selected for DUS testing were relatively stable across the locations of the two mega-environments. Female and male farmers independently identified nine traits and ranked them according to their importance for use by breeders in breeding nurseries; both farmer groups listed the same traits, with slight differences in their ranking. Marketable vegetable yields were positively correlated with each of plant height and leaf length in most of the locations. Female and male farmers' selection scores were also positively correlated with yield and with each other, indicating similarity of preferences for amaranth variety type between the two gender groups. Participation in variety selection of the two gender groups, however, gives equal platform for both genders and helps promote gender equality.

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