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Stability, performance and participatory evaluation of potato varieties under rain-fed and irrigation conditions at Southeast, Ethiopia

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ABSTRACT

The goal of potato breeding is to develop widely adaptable, highly productive cultivars that farmers would prefer. The objective of this study was to evaluate the performance and stability of potato varieties linking the preferences of smallholder farmers in rain-fed and irrigated environments. Using a randomized complete block design in three replicates, twelve potato cultivars were assessed in 10 settings in Southeast Ethiopia during the Meher and Belg seasons in 2019 and 2020. The environments, genotypes, and GEI all revealed significant differences ($p<0.001$) in the pooled analysis of the variance of tuber yield. The tuber yield variances for GEI, environment, and genotypic impacts were 15.48%, 7.61%, and 59.49% explained by the AMMI analysis, respectively. The environments were grouped into three distinct categories. A total of 99.6% of the variance was the cumulative contribution of PC1, PC2, PC3, PC4, and PC5 sharing 80.8%, 11.3%, 4.3%, 2.2%, and 1.0%, respectively High-yielding and widely adapted were Gera, Gudanie, Bubu, Belete, Shenkolla, Guassa, and Maracharre varieties, according to the AMMI, BLUP, GGE biplot, and WAAS. However, dynamic types that were particularly affected by environmental variations include Jalenie, Dagim, Gorebella, Awash, and Zemen. A stability measure of metric and preference based on various traits identified Gudanie and Guassa varieties. The scores of the small holder farmers were consistent throughout the test environments. The canonical correlation analysis indicated the significant association between the metric traits collected by the breeder and the small- holder farmer preferences. The study provides baseline data for potato breeding, and the varieties must be evaluated in the nation's mega-environments for additional recommendations.

Keywords: AMMI, BLUP, Canonical correlation, GGE, WAAS

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Introduction

Potato (*Solanum tuberosum* L.) is the fourth most important non-grain human food and most productive food security crop in terms of yield, starch, dry matter, calories, quality protein per unit area, and short crop cycle (Slater *et al.*, 2014; Kolech *et al.*, 2017; Devaux *et al.*, 2021; Asnake *et al.*, 2023). It is a flexible crop grown worldwide in different agro-ecologies from sea level up to 4,700 m.a.s.l. (Anonymous, 2017; Burke, 2017; Batool *et al.*, 2020; Calıskan *et al.*, 2022). Potatoes are produced globally on 16,494,810 hectares of land devoted to farming, with an estimated production of 359,071,407 tons (Anonymous, 2020). In Africa, South Africa, Ethiopia, Mozambique, the Democratic Republic of the Congo, Burundi, Rwanda, Cameroon, and Nigeria are home to more than seven million smallholder farmers of potatoes (Abdulwahab *et al.*, 2016). Sub-Saharan African countries grew potatoes approximately on 1.47 million ha of land in 2018, but yields varied greatly across the countries (Anonymous, 2019).

Potato leads the list of root and tuber crops production in Ethiopia (Anonymous, 2022). The Ethiopian national average yield of potatoes is 16.69 ton ha^{-1} and they are cultivated on roughly 78,478.72 ha of land in peasant holdings with an estimated harvest of 1,309,566.8 ton (Anonymous, 2022). Of eighteen agro-ecologies in the country, the majority of them are ideal for potato production in *Belg*, *Meher*, *Belmehr*, and *Mesino* seasons (Kolech *et al.*, 2015; Tessema *et al.*, 2020; Tessema *et al.*, 2022). The seasons cover from January to May or June, May or June to October, March or April to August, and September to December, respectively (Kolech *et al.*, 2015). Smallholder farmers grow potatoes in Arsi and West Arsi in Belg and Meher seasons, however, the majority of farmers shifted their production to Belg season to minimize the late blight pressure and acquire good market prices (Kolech *et al.*, 2015).

Potato production is limited by several factors. These confine diseases, post-harvest handling loss, storage facilities, and insufficient supply of clean seed tubers, abiotic stresses, pests, and poor agronomic practices (Bezabih and Mengistu, 2011; Labarta, 2013; Krijger and Waals, 2020). More than 39 potato varieties have been released for large-scale production, through the contribution of the Ethiopian Institute of Agricultural Research, regional research institutes, higher learning institutions, and private companies (Anonymous, 2022). Breeders select and register these genotypes with a prime focus on yield potential, late blight resistance, earliness, and being stable and broadly adaptable over a range of environments, predominantly during the *Meher* season (Kolech *et al.*, 2015; Asefa *et al.*, 2016; Kolech *et al.*, 2017; Tsagaye *et al.*, 2023). Even though the improved varieties have been reported to be high-yielders and resistant to late blight, their adoption by farmers has been low in most areas, as reasoned by Abebe *et al.* (2013) as lacking the attributes desired by farmers. This is the tendency of farmers to depend on local varieties because of the perceived easier crop management and better stew quality attributes (Abebe *et al.*, 2013). The adoption of new varieties was limited as the breeding process did not take into account the inclusion of farmer preferences. As a result, a limited number of new varieties are grown in the country. Another impediment that often arises is that varieties are less adaptive in specific conditions, which affects the adoption of the varieties by the farmers. Therefore, the objective of the present study was to evaluate the stability and performance of potato cultivars joining smallholder farmers' preferences under rain-fed and irrigation conditions.

Methodology

Test varieties and environments

Twelve released potato varieties were evaluated at 3 and 2 locations under rain-fed and irrigation conditions in the *Belg* and *Meher* seasons from 2019 to 2020, respectively. The experiment in the *Belg* season was conducted with supplementary irrigation at Kulumsa Agricultural Research Center and Sagure farmer's field. Description of potato varieties and the test environments were presented in Tables 1 and 2, respectively.

Experimental layout and design

A Randomized complete block design with three replications was employed to evaluate the 12 potato varieties. Each variety was planted at an inter and intra-row spacing of 75 cm and 30 cm of 1.8-2.0 t ha^{-1} in a plot of four rows of 40 tubers on a plot size of 3m×3m. Planting and harvesting of evaluated materials were carried out from the end of January to mid-May and from mid-June to the first week of November, respectively. The harvestable two central rows were 3.6 m^2 areas. Fertilizer application and other agronomic practices were applied as per the local recommendations for each testing location.

Agronomic, quality and preference data collection

Data on phenological, agronomic and quality traits such as days to 50% emergency (DE), days to 50% flowering (DF) and days to 50% maturity (DM), number of main stems per hill (STN), plant height (PH), marketable tuber yield (MTY), unmarketable tuber yield (UNMTY), total tuber yield (TTY), dry matter content (DMC), specific gravity (SG), starch content, and diseases were recorded.

To calculate the specific gravity of tubers, five kg of randomly taken potato tubers were measured in air and water. The specific gravity of tubers was calculated using the following formula suggested by Kleinkopf *et al.* (1987).

$$\text{Specific gravity (gcm}^{-3}) = \frac{\text{weight in air}}{\text{weight in air} - \text{weight in water}} \text{ (1).}$$

Total starch content (g/100g) was estimated from specific gravity. Starch (%) = 17.565 + 199.07 × (specific gravity -1.0988) (2) (Hassel *et al.*, 1997 as cited in Mohammed, 2016). In addition, the dry matter content was calculated using the formula proposed by Kleinkopf *et al.* (1987) -214.9206 + 218.1852 (specific gravity) (3).

Table 1. List of potato varieties included in the performance evaluation during the 2019 and 2020 cropping seasons.

No.	Variety/ genotype name	Pedigree	Registration year	Releasing center/Institute	Altitude requirements (m.a.s.l)
1	Jalenie	CIP-384321.19	2002	HARC/EIAR	1600-2800
2	Gudanie	CIP-386423.13	2006	HARC/EIAR	1600-2800
3	Belete	CIP-393371.58	2009	HARC/EIAR	1600-2800
4	Shenkolla	KP- 90134.5	2005	AwARC/ SARI	1700-2700
5	Gera	KP-90134.2	2003	ShARC/ ARARI	2700-3200
6	Zemen	AL-105	2001	Haramaya University	1700-2000
7	Guassa	CIP-384321.9	2002	Adet ARC/ ARARI	2000-2800
8	Awash	CIP-378501.3	1991	HARC/EIAR	1500-2000
9	Gorebella	CIP-382173.12	2002	ShARC/ ARARI	1700-2400
10	Mara charre	CIP-389701-3	2005	AwARC/ SARI	1700-2700
11	Bubu	CIP-384321.3	2011	Haramaya University	1700-2000
12	Dagim	CIP-396004.337	2013	Adet ARC/ ARARI	2000-2800

Source: Anonymous (2022), EIAR = Ethiopian Institute of Agricultural Research, ARC = Agricultural Research Centre, HARC=Holetta Agricultural Research Centre, AwARC= Awassa Agricultural Research Centre, ShARC= Sheno Agricultural Research Centre, ARARI = Amhara Regional Agricultural Research Institute, SARI= Southern Agricultural Research Institute, m.a.s.l = meter above sea level.

A participatory variety selection scheme adopted from the Africa Rice Center (Anonymous, 2010), including a field experiment, was conducted on farmer fields at Sagure and in research fields at Bekoji, Asasa, Kofele, and Kulumsa, south-east Ethiopia. Both farmers and breeders participated in the management of the field trials. During the *Belg* season, oxen (farmer's practice) were used for planting and harvesting at Sagure. For *Meher* season, planting was done manually in ridges, following the national research recommendations. A fungicide, Redomil Gold, was sprayed at a rate of 4 kg ha^{-1} twice at Bekoji, Asasa, and Kofele once during the *Belg* (Sagure and Kulumsa) season.

Field performance (stand or vigor), the growth habit of the variety (leaf size, stem thickness, uniformity in flowering, and growth habit), late blight resistance, insect pest resistance (specifically at Asasa, Sagure, and Kulumsa), early bulking, drought tolerance (Asasa), tuber yield potential, tuber characteristics (tuber size, color, sprout number, and eye depth), culinary qualities (taste, suitability for boiled potato, stew, and chips), and shelf life were the main selection criteria for participatory selection of potato cultivars. Data were recorded based on the ratings of the chosen preference traits common to each environment after consulting.

Table 2. Descriptions of the five testing environments in Southeast Ethiopia.

Testing environments	Growing season	Geographical position		Altitude (m.a.s.l.)	Temperature (°C)		Average rainfall (mm)	Soil type	Soil PH
		Latitude (N)	Longitude (E)		Minimum	Maximum			
Bekoji	*Meher*	07°31′22″	39°14′46″	2780	3.80	20.40	1020	Clay soil (Nitosols)	5.23
Asasa	*Meher*	07°06′12″	39°11′32″	2367	5.80	24.00	620	Silt loam	6.50
Kofele	*Meher*	07°04′27″	38°46′45″	2660	7.10	18.00	1211	Clay loam	5.20
Sagure	*Belg*	07°45′0″	39°9′0″	2568	10.00	20.00	1239	Vertisols	-
Kulumsa	*Belg*	08°01′00″	39°09′32″	2200	10.50	23.20	832	Eutric Nitosol	6.00

Statistical analysis

The combined analysis of variance was first carried out across the test locations for marketable tuber yield. Metan-package in comprehensive free R software was employed to calculate the most stable statistics (Olivoto and Lúcio, 2020; Anonymous, 2024). The statistics used to assess the stability, genetic merit, and adaptability of genotypic mean tuber yield were the additive main effect and the multiplicative interaction (AMMI) (Yan, 2011), best linear unbiased prediction (BLUP) (Olivoto *et al.*, 2019), genotype-genotype by environment biplot (GGE), and weighted average of absolute scores (WAAS) (Olivoto *et al.*, 2019). The corrplot (Murdoch and Chow, 1996; Friendly, 2002) and CCA package (González *et al.*, 2008) were used to display and calculate the correlation within and between the sets of metric and preference traits.

Results and Discussion

AMMI Analysis of Variance

AMMI analysis of variance pooled data over the 10 environments of marketable tuber yield showed highly significant differences in environment (E), genotypes (G), and their interaction (GEI) ($P < 0.001$) (Table 3).

Table 3. AMMI analysis of variance for marketable tuber yield of 12 potato varieties evaluated across 10 environments in the southeast of Ethiopia.

Source	Df	SS	MS	F value	Probability	% Explained
ENV	9	4859.17	539.91	30.06	1.04E-09	7.61
REP(ENV)	20	359.27	17.96	4.49	7.52E-09	17.42
GEN	11	38004.68	3454.97	864.34	2.9E-174	59.49
GEN:ENV	99	9890.66	99.91	24.99	5.87E-81	15.48
PC1	19	7993.20	420.69	105.25	0.0000	80.82
PC2	17	1118.85	65.81	16.47	0.0000	11.31
PC3	15	425.74	28.38	7.10	0.0000	4.30
PC4	13	219.10	16.85	4.22	0.0000	2.22
PC5	11	97.64	8.88	2.22	0.0144	1.00
PC6	9	25.55	2.84	0.71	0.6995	0.30
PC7	7	10.53	1.50	0.38	0.9134	0.10
PC8	5	0.03	0.01	0.00	1.0000	0.00
PC9	3	0.00	0.00	0.00	1.0000	0.00
Residuals	220	879.39	4.00			
Total	458	63883.84	139.48			

ENV: Environments, REP: replication, GEN: genotypes (varieties), GEN × ENV: genotype-by-environment interaction, Df: Degrees of freedom, SS: sum of squares, MS: mean squares.

A number of scholars (Fufa, 2013; Gedif and Yigzaw, 2014; Sood *et al.*, 2020; Scavo *et al.*, 2023) reported similar results suggesting the existence of wide capriciousness among environments, genotypes, and the chance of selecting stable genotypes. This distinguishes the influence of changes in the environment on the marketable tuber yield performance of potato varieties in the two cropping seasons.

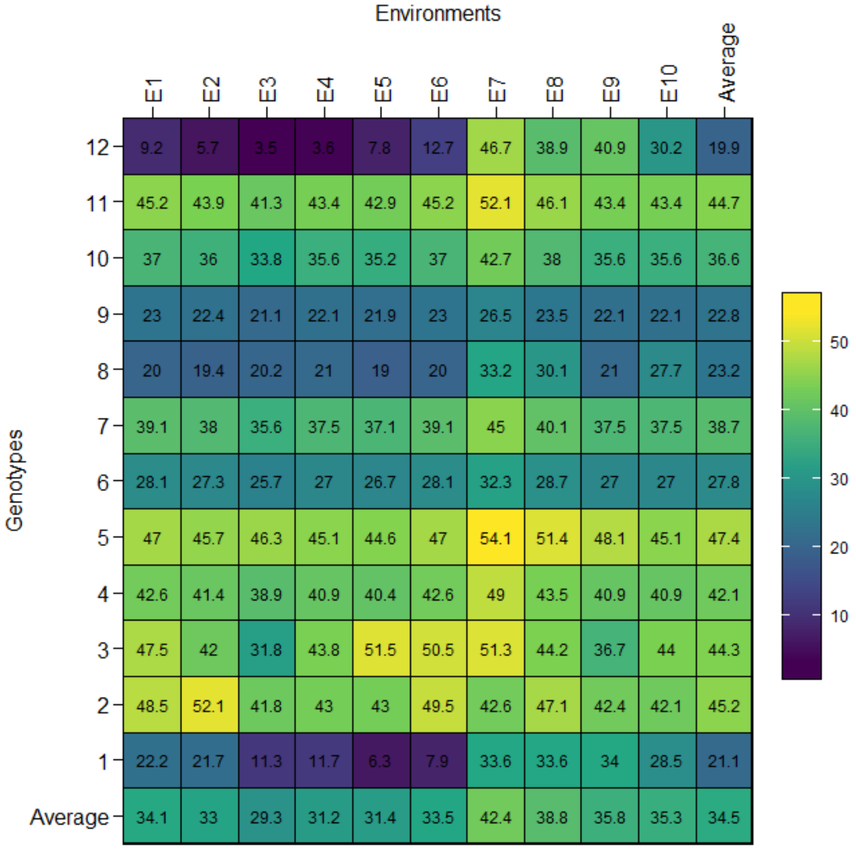
Similarly, the genotype and environmental factors, i.e., years, seasons, and environments, had a significant main effect ($P < 0.001$). However, a high marketable tuber yield variation was explained varieties, which indicated that the varieties are diverse and a major part of the variation in tuber yield can result from varietal differences, followed by GEI and environmental effects accounting for relative magnitudes of 59.49%, 15.48%, and 7.61%, respectively (Table 3). The significant GEI sum of squares is further partitioned into nine interaction principal component axes (IPCAs). The first five significant IPCAs explained 99.6% of the variations in the total sum of squares due to the interaction, each accounting for 80.8%, 11.3%, 4.3%, 2.2%, and 1.0% of the GEI variation, respectively.

Mean performance of potato varieties for phenology and growth traits

Statistically significant variations for days to 50% emergence, days to 50% flowering, and days to 50% physiological maturity were observed among potato varieties in both the *Meher* and *Belg* seasons (Table 4). The potato varieties took 19.94 days (Guassa) to 27.11 days (Zemen) to attain 50% emergency in the *Meher* season and 16.17 days (Bubu) to 24.67 days (Dagim) to emerge in the *Belg* season. Potato varieties require 62.94 days (Jalenie) to 76.06 days (Bubu) and 51.67 days (Awash) to 65.08 days (Zemen) to attain 50% flowering in the *Meher* and *Belg* seasons, respectively (Table 4). In the *Meher* and *Belg* seasons, the earliest varieties were Dagim (99.61 days) and Awash (87 days) and the late varieties were Belete (114.33 days) and Jalenie (104.5 days) attain 50% physiological maturity, respectively. Tsagaye *et al.* (2023) reported akin results for 10 potato clones including Gudanie, Belete and Dagim as standard checks at Bekoji and Kofele, Southeast Ethiopia.

The longest plant was observed from varieties Shenkolla, Gera and Bubu with mean values of 86.89 cm, 82.30 cm and 78.18 cm, respectively (Table 4). Relatively, shorter plant height was recorded from potato varieties under irrigation conditions the highest plant height was scored from Dagim (79.20 cm) and the shortest was from Gorebella (47.41 cm). In both seasons (2019 and 2020) Kofele is the best environment for the PH in *Meher season* and Kulumsa for *Belg season*, respectively (Table 4). In accordance with the present study, Amenu *et al.* (2022); Tessema *et al.* (2022); Abdena and Bedassa (2023); Tsagaye *et al.* (2023) reported wider variations in plant height. The shortest magnitude of plant height was noted from Asasa. The environments contributed significantly to the different performance of genotypes across test locations, resulting in either crossover or non-crossover G×E. Non-crossover interaction is a score of genotypes that remain consistent across environments, however cross-over is a substantial shift in genotype performance between test sites.

The analysis of variance revealed highly significant differences ($p < 0.001$) in the number of stems per hill among the tested potato varieties at the test locations (Table 4). The results revealed that numerically, the number of stems per hill ranges from 2.51 at the Maracharre variety to 8.40 at the Awash variety. This variation shows the existence of high genetic variation among the tested potato varieties used for this experiment. The reason for the number of stems per hill variation happening among accession is probably related to the variation of local environmental conditions among individual varieties and the study of environmental and seasonal differences. In line with the present finding (Amenu *et al.*, 2022; Tessema *et al.*, 2020; Tessema *et al.*, 2022; Abdena and Bedassa, 2023; Tsagaye *et al.*, 2023; Daemo and Ashango, 2024), they reported the wide variation in mean values of the number of stems per hill in different potato varieties in different study sites of Ethiopia.



	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Average
12	9.2	5.7	3.5	3.6	7.8	12.7	46.7	38.9	40.9	30.2	19.9
11	45.2	43.9	41.3	43.4	42.9	45.2	52.1	46.1	43.4	43.4	44.7
10	37	36	33.8	35.6	35.2	37	42.7	38	35.6	35.6	36.6
9	23	22.4	21.1	22.1	21.9	23	26.5	23.5	22.1	22.1	22.8
8	20	19.4	20.2	21	19	20	33.2	30.1	21	27.7	23.2
7	39.1	38	35.6	37.5	37.1	39.1	45	40.1	37.5	37.5	38.7
6	28.1	27.3	25.7	27	26.7	28.1	32.3	28.7	27	27	27.8
5	47	45.7	46.3	45.1	44.6	47	54.1	51.4	48.1	45.1	47.4
4	42.6	41.4	38.9	40.9	40.4	42.6	49	43.5	40.9	40.9	42.1
3	47.5	42	31.8	43.8	51.5	50.5	51.3	44.2	36.7	44	44.3
2	48.5	52.1	41.8	43	43	49.5	42.6	47.1	42.4	42.1	45.2
1	22.2	21.7	11.3	11.7	6.3	7.9	33.6	33.6	34	28.5	21.1
Average	34.1	33	29.3	31.2	31.4	33.5	42.4	38.8	35.8	35.3	34.5

Fig. 1. Heat map depicting the mean performance of potato varieties at the 10 environments. The numbers (1-12) represent Genotypes (varieties) as depicted in Table 1. E1=Bekoji 2019, E2= Bekoji 2020, E3=Asasa 2019, E4= Asasa 2020, E5= Kofele 2020, E6 = Kofele 2019, E7= Sagure 2019, E8= Sagure 2020, E9= Kulumsa 2019, E10= Kulumsa 2020.

Mean performance of potato varieties for yield and yield-related traits

The mean marketable tuber yield (MTY) (t ha^{-1}), of potato varieties across ten environments was presented in Figure 1. On average, genotypes Gera, Gudanie, Bubu, Shenkolla, Belete, and Guassa gave the highest mean MTY across environments. Varieties Jalenie and Dagim had the lowest mean MTY of all tested varieties across environments (Fig. 1). With the exception of Dagim, it has produced a higher MTY in Sagure 2019, Sagure 2020, and Kulumsa 2019. The highest MTY was observed at the Sagure 2019 cropping season, followed by the Sagure 2020 season (Fig. 1). This differential performance of the varieties could be the influence of the late blight in the *Meher* season compared to the *Belg* season, and this is the reason why farmers have shifted their production to the *Belg* season in the test environments. The average MTY of the tested potato varieties over the three and two environments was 32.08 t ha^{-1} and 38.08 t ha^{-1} at *Meher* and *Belg* seasons, respectively. Variety Gudanie had the highest average MTY (46.33 t ha^{-1}), followed by Gera (45.95 t ha^{-1}), while variety Dagim gave the lowest MTY (7.07 t ha^{-1}) (Table 4) in the main cropping season *Meher*. Under irrigation conditions, Gera (49.69 t ha^{-1}) produced the highest MTY, followed by Bubu (46.24 t ha^{-1}) and the lowest yield was recorded from Gorebella (23.55 t ha^{-1}). This analysis was closely related to previous studies by Amenu *et al.* (2022); Tessema *et al.* (2022); Tsagaye *et al.* (2023) Daemo and Ashango (2024), who showed significant variations among potato genotypes in marketable and unmarketable tuber weight. They added that marketable tuber number was an important trait in the potato crop from an economic point of view.

Mean performance of potato varieties for specific gravity, dry matter and starch contents

Potato varieties showed highly significant differences (*p<0.001*) for specific gravity, dry matter and starch content in all environments (at each location and growing season) and combined over growing seasons (*Meher* and *Belg*). The combined analysis of variance for each location over growing seasons revealed that tuber dry matter content was significantly influenced by variety and the interaction of variety x season while it was significantly influenced by variety and season (Table 4). The presence of wide variations among varieties for tuber specific gravity, dry matter and starch contents indicated the genetic factor was important in influencing the tuber internal quality traits. The observed differences are a virtuous opportunity for the producers to select the varieties for production that fit the market demand. Numerous other scholars also reported the presence of significant differences among potato cultivars for those tuber quality traits (Abebe *et al.*, 2013; Mohammed, 2016). Tsagaye *et al.* (2023) also reported comparable results for experiments conducted at Bekoji and Kofele among potato clones for specific gravity.

Table 4. Mean performance of potato varieties for 9 agronomic and 3 quality traits evaluated in Southeast Ethiopia in 2019 and 2020.

Meher season												
Varieties	DE	DF	DM	STN	PH	MTY	UNMTY	TTY	ATW	SG	DMC	Starch
Jalenie	21.50^{e}	62.94^{i}	106.67^{d}	5.33^{b}	53.36^{g}	13.52^{i}	1.73^{i}	15.25^{h}	66.17^{g}	1.09^{cde}	23.61^{cde}	16.46^{cde}
Gudanie	23.61^{cd}	67.17^{g}e	109.89^{b}	5.87^{a}	77.24^{c}	46.33^{a}	4.20^{f}	50.53^{a}	117.08^{a}	1.09^{de}	23.39^{de}	16.26^{de}
Belete	24.56^{bc}	71.39^{d}	114.33^{a}	3.74^{d}	71.97^{d}	44.51^{b}	4.70^{e}	49.21^{b}	110.24^{b}	1.09^{e}	22.66^{e}	15.60^{bc}
Shenkolla	21.89^{e}	73.17^{f}	110.11^{b}	6.28^{a}	86.89^{a}	41.12^{c}	2.05^{i}	43.17^{d}	100.87^{c}	1.10^{bc}	24.50^{bc}	17.27^{bc}
Gera	21.78^{e}	70.00^{ab}	108.33^{c}	5.98^{a}	82.30^{b}	45.95^{a}	2.92^{h}	48.87^{b}	103.02^{c}	1.10^{bcd}	24.33^{bcd}	17.12^{bcd}
Zemen	27.11^{a}	75.78^{c}	113.61^{a}	2.51^{f}	76.38^{c}	27.12^{f}	3.43^{g}	30.55^{e}	56.34^{h}	1.11^{a}	26.97^{a}	19.53^{a}
Guassa	19.94^{f}	74.56^{g}	113.89^{a}	4.83^{c}	67.42^{e}	37.74^{d}	8.14^{a}	45.87^{c}	79.51^{e}	1.10^{bcd}	24.50^{bc}	17.27^{bc}
Awash	27.00^{a}	67.39^{c}	103.22^{e}	4.18^{d}	58.00^{f}	19.93^{h}	7.42^{b}	27.35^{f}	54.80^{h}	1.10^{bcd}	24.81^{b}	17.55^{b}
Gorebella	27.00^{a}	74.33^{bc}	101.78^{e}	2.93^{ef}	55.60^{fg}	22.24^{g}	0.72^{j}	22.96^{g}	72.89^{f}	1.10^{bcd}	24.36^{bcd}	17.15^{bcd}
Mara charre	25.17^{b}	74.72^{a}	105.28^{d}	2.51^{f}	53.79^{g}	35.76^{e}	6.47^{c}	42.24^{d}	54.11^{h}	1.11^{a}	26.97^{a}	19.53^{a}
Bubu	23.11^{d}	76.06^{a}	113.00^{a}	3.25^{e}	78.18^{c}	43.66^{b}	5.37^{d}	49.03^{b}	86.72^{d}	1.11^{a}	26.97^{a}	19.53^{a}
Dagim	24.06^{dc}	65.17^{h}	99.61^{f}	6.13^{a}	58.70^{f}	7.07^{j}	1.01^{j}	8.08^{i}	64.29^{g}	1.09^{e}	22.91^{e}	15.82^{e}
Mean	23.89	71.06	108.31	4.46	68.32	32.08	4.01	36.09	80.50	1.10	24.67	17.42
CV	6.76	2.35	2.06	16.73	6.90	5.72	18.24	5.46	8.66	0.69	6.67	8.61
LSD	1.07	1.10	1.47	0.48	3.11	1.21	0.48	1.30	4.60	0.01	1.08	0.99
	Belg season											
Jalenie	21.75^{bc}	61.25^{c}	104.50^{a}	6.16^{c}	63.98^{d}	32.46^{f}	11.06^{ab}	43.52^{f}	113.00^{d}	1.^{09ef}	21.83^{ef}	14.84^{ef}
Gudanie	21.33^{c}	53.67^{f}	101.20^{bc}	5.31^{de}	68.10^{c}	43.58^{c}	6.66^{de}	50.23^{bc}	125.43^{c}	1.09^{de}	22.85^{de}	15.76^{de}
Belete	22.67^{b}	55.33^{e}	100.00^{c}	4.74^{e}	78.10^{a}	44.04^{c}	10.24^{g}	54.28^{a}	155.43^{a}	1.09^{cd}	23.02^{cd}	15.92^{cd}
Shenkolla	17.33^{ef}	62.50^{b}	94.33^{ef}	7.22^{b}	73.87^{b}	43.56^{c}	2.29^{f}	45.85^{de}	142.62^{b}	1.10^{bc}	24.06^{bc}	16.87^{bc}
Gera	16.58^{fg}	60.00^{d}	93.00^{f}	6.87^{b}	70.00^{c}	49.69a	3.25^{f}	52.94^{a}	109.63^{d}	1.10^{bc}	24.06^{bc}	16.87^{bc}
Zemen	18.25^{de}	65.08^{a}	97.42^{d}	2.89^{g}	64.05^{d}	28.74^{g}	3.84^{f}	32.58^{h}	108.35^{d}	1.11^{a}	26.68a	19.26^{a}
Guassa	16.83^{fg}	63.92^{a}	97.67^{d}	5.55^{cd}	57.29^{e}	40.06^{d}	9.12^{c}	49.17^{c}	59.42^{h}	1.10^{bc}	24.06^{bc}	16.87^{bc}
Awash	18.67^{d}	51.67^{g}	87.00^{h}	8.40^{a}	57.13^{e}	28.02^{g}	11.83^{a}	39.85^{g}	84.00^{f}	1.08^{f}	21.65^{f}	14.67^{f}
Gorebella	17.92^{de}	62.08^{bc}	87.50^{h}	3.37^{fg}	47.41^{f}	23.55^{h}	0.80^{h}	24.35^{i}	87.33^{ef}	1.10^{b}	24.58^{b}	17.34^{b}
Mara charre	16.75^{fg}	63.92^{a}	89.58^{g}	2.89^{g}	45.81^{f}	37.93^{e}	7.20^{d}	45.13^{ef}	76.88^{g}	1.11^{a}	26.68^{a}	19.26a
Bubu	16.17^{g}	65.00^{a}	96.00^{de}	3.73^{f}	67.57^{c}	46.24^{b}	6.00^{e}	52.25^{ab}	57.53^{h}	1.11^{a}	26.68a	19.26^{a}
Dagim	24.67^{a}	59.67^{d}	102.17^{b}	5.89^{cd}	79.20^{a}	39.16^{de}	8.83^{c}	47.99^{cd}	91.65^{e}	1.09^{def}	22.73^{def}	15.65^{def}
Mean	19.08	60.34	95.86	5.25	64.38	38.08	6.76	44.84	100.94		24.07	16.88
CV	6.32	2.41	2.46	15.71	5.54	5.83	16.4	6.35	7.97	0.57	5.66	7.36
LSD	0.98	1.18	1.91	0.67	2.89	1.80	0.89	2.31	6.53	0.01	1.10	1.01

The AMMI-2 bi-plot analyses of MTY (t ha^{-1}) of twelve potato varieties evaluated in ten environments are shown in Figure 2a. For MTY, the percentage of variation contributed by the IPCA-1 and IPCA-2 axes was 80.8% and 11.3%, respectively (Fig. 2a). Potato varieties Bubu, Guassa, Shenkolla, Gudanie, Gorebella, Belete, Maracharre, and Gera are broadly adaptable as they were located closer to the center of the bi-plot. Varieties Dagim and Jalenie are located furthest from the point of origin, showing specific adaptation to the environments within their proximity on the bi-plot.

Moreover, Belete, Gudanie, Shenkolla, Gera, Guassa, Maracharre, and Bubu had above-average yields and were located on the acute angle of PC1 (Fig. 2a and b). Varieties located on the right-hand side of the bi-plot were positively correlated with the environments on the same side (Fig. 2c).

Based on this analysis, environments Sagure 2019 and 2020 and Kulumsa 2019 and 2020 were considered highly discriminating and had similar discriminating ability of the site since they had longer vectors (Fig. 2d). Environments Bekoji 2019, Asasa 2019, Kofele, 2019, Asasa 2020, Bekoji 2020, and Kofele 2020, were highly positively correlated, indicating that genotypes ranked similarly concerning MTY in these environments. This suggested that these environments might form part of the same mega-environment.

Table 5. Stability analysis of potato varieties across 5 environments from 2019-2020 using different stability indexes.

AMMI-based stability indexes														
Varieties	Y	ASTAB	ASI	ASV	AVAM GE	DA	DZ	EV	FA	MASI	MASV	SIPC	ZA	WAAS	BLUPg
Jalenie	21.09	19.47	2.40	21.02	69.70	25.01	0.95	0.23	625.49	2.40	22.27	8.31	0.43	2.80	-13(12)
Gudanie	45.23	10.43	1.50	13.21	41.62	16.12	0.87	0.19	259.94	1.51	14.14	6.38	0.27	1.76	10.40(2)
Belete	44.32	14.94	1.30	11.38	46.88	18.21	0.93	0.22	331.67	1.30	14.15	7.17	0.28	1.70	9.53(4)
Shenkolla	42.09	0.72	0.60	5.28	16.24	5.54	0.16	0.01	30.68	0.60	5.38	1.38	0.09	0.64	7.47(5)
Gera	47.45	1.43	0.34	2.99	11.81	4.97	0.33	0.03	24.68	0.34	4.12	2.08	0.07	0.43	11.2(1)
Zemen	27.77	1.09	0.76	6.67	20.85	6.97	0.18	0.01	48.56	0.76	6.78	1.63	0.12	0.81	-5.91(8)
Guassa	38.66	0.73	0.63	5.51	17.01	5.72	0.15	0.01	32.73	0.63	5.59	1.27	0.09	0.66	3.80(6)
Awash	22.50	2.92	0.08	0.73	15.11	5.78	0.52	0.07	33.35	0.11	4.11	2.58	0.04	0.18	-10.4(9)
Gorebella	22.76	1.33	0.82	7.19	22.56	7.57	0.21	0.01	57.29	0.82	7.32	1.93	0.13	0.89	-11.5 (10)
Mara charre	36.63	0.79	0.65	5.75	17.79	5.96	0.15	0.01	35.57	0.66	5.83	1.26	0.10	0.68	1.72(7)
Bubu	44.69	0.71	0.58	5.05	15.46	5.34	0.17	0.01	28.51	0.58	5.15	1.44	0.09	0.62	9.54(3)
Dagim	20.04	36.90	4.68	41.07	127.30	42.29	0.95	0.23	1788.09	4.68	41.25	8.52	0.70	4.94	-12.9(11)

Y= mean of the response variable, ASTAB= AMMI Based Stability Parameter, BLUPg= Best linear unbiased prediction of genotypes (the numbers in bracket represents the rank of the varieties based on their tuber yield stability), WAAS = Weighted average of absolute scores, MASI = Modified AMMI Stability index, ASI = AMMI Stability Index, ASV = AMMI-stability value, MASV = Modified AMMI Stability Value, ZA = Absolute Value of the Relative Contribution of IPCs to the Interaction, DZ = Zhang's D Parameter, EV = Sums of the Averages of the Squared Eigenvector Values, SIPC = Sums of the Absolute Value of the IPC Scores, AVAMGE =Sum Across Environments of Absolute Value of GEI Modelled by AMMI, DA = Annicchiarico's D Parameter values, FA = Stability Measure Based on Fitted AMMI Model.

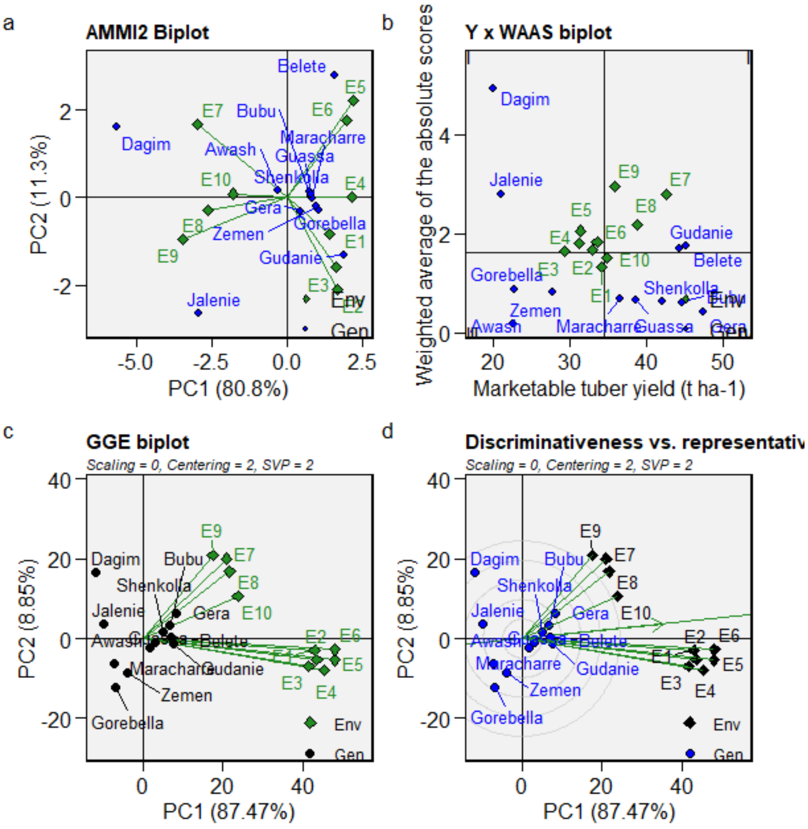


Fig. 2. (a) AMMI-2 biplot showing the main effects vs stability (PC1 and PC2) view of both genotypes and environments on marketable tuber yield performance and stability of 12 potato genotypes using, (b) biplot of Weighted average of absolute scores (WAAS), (c) genotype plus genotype by environment (GGE) and (d) discriminativeness vs representativeness of the 10 environments.

Mega-environments analysis using GGE bi-plots

The polygon assessments of the GGE biplot for MTY are shown in Figure 3c. In each biplot, different mega-environments (MGEs) were grouped into sectors. Environments within the same MGE were assumed to have a similar effect on genotype performance and were considered a homogeneous cluster. Similarly, genotypes within the same MGE were assumed to have a similar response to the environments located in the MGE sector. The genotype located at the vertex of the sector was considered the best-performing variety in the MGE. For MTY (Fig. 3c), PC-1 explained 87.47% of the total variation; however, PC-2 explained 8.85%, with both axes contributing 96.32% of the total variation. Perpendicular lines were drawn to each side of the polygon, all lines starting from the bi-plot origin (Fig. 3c). In this analysis, three mega-environments were found: environments Sagure 2019(E7), Sagure 2020(E8), and Kulumsa 2019(E9) assembled into MGE-1; environment Kulumsa 2020(E10) fell into a separate MGE-2; Bekoji 2019(E1), Bekoji 2020(E2), Asasa 2019(E3), Asasa 2020(E4), Kofele 2019(E5), and Kofele 2020(E5) are MGE-3. Potato variety Gera was the highest-yielding variety in MGE-1. Variety Bubu, Belete, and Guassa won in the MGE-2. Variety Gudanie was positively correlated with the environment Bekoji 2020(E2) site and was the winning genotype in MGE-3. Yan (2007) suggests that an ideal genotype should have both high mean performance and high stability within a mega-environment. The arrow shown on the axis of the AEC abscissa compares and ranks the performance of the test genotypes relative to the "ideal genotype".

Variety yield and stability using GGE bi-plots

The MTY, PC-1, explained 87.47% of the variation, and PC-2 explained 8.85%, for a total of 96.32% of the variation (Fig. 3a and b). Varieties Gera and Gudanie were the ideal varieties/genotypes, and, therefore, they were considered the most desirable varieties/genotypes of all the evaluated varieties, followed by Bubu, Belete, and Shenkolla varieties.

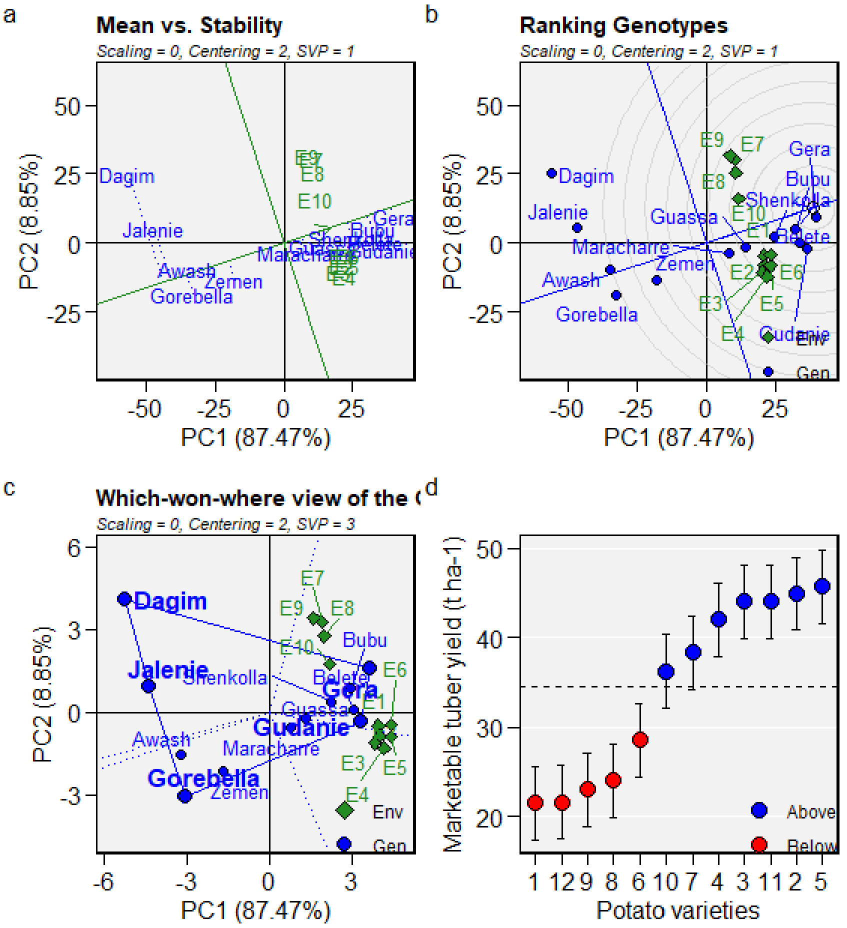


Fig. 3. Average-environment coordination views to show (a) means vs stability biplot analysis, (b) Ranking genotypes for tuber yield performance relative to an ideal genotype, (c) Which-won-where view the genotypes and (d) BLUP ranks of genotypes and predicted stability 12 potato varieties. Blue and red circles represent the genotypes that had BLUP above and below BLUP means, respectively. The numbers (1–12) represent the potato varieties illustrated in Table 1.

Environment discriminating ability and representativeness using GGE bi-plot

A similar analysis was applied for an environment-focused biplot, which represents the ideal environment within a mega-environment. The ideal environment must have high discriminating power and representativeness. In this study, the ideal test environments were Sagure 2019 and Sagure 2020 environments (Fig. 1, 2d, 3a, and 3b). Test environments that had proximity to the ideal environment on the axis were positively correlated with genotypes closer to them. Each environment had a higher interaction with the varieties/genotypes in the test environment in influencing the performances of potato varieties. The purpose of validation of the test environment is to identify ideal environments that effectively identify superior genotypes for a mega-environment.

Gudanie and Guassa selected varieties by a multi-trait-based stability index of metric and farmer's preference traits as presented in the radar chart (Fig. 4). This selection was based on the performance of the varieties through marketable tuber yield, average tuber weight, field performance (stand or vigour), late blight resistance score of the farmers, culinary qualities of the varieties, and the overall score values of the preferences.

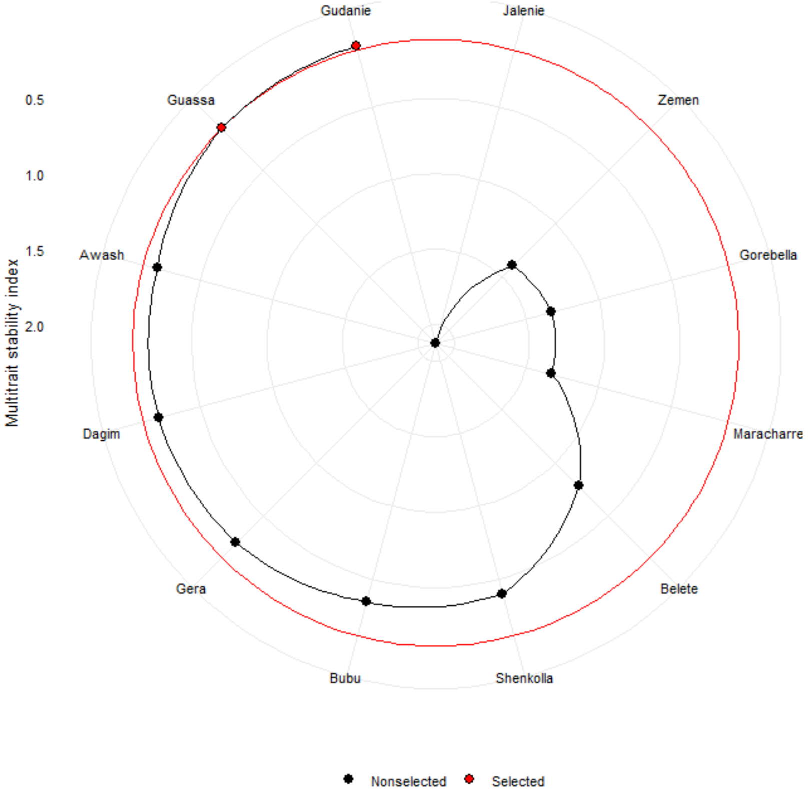


Fig. 4. Potato variety selection based on multi-trait stability index of some tuber yield and preference traits. The red dots represent the selected potato varieties based on varietal performance and preferred traits by the farmers.

Yan *et al.* (2000) defined an "ideal" genotype based on both mean performance and stability, and the genotype types can be ranked based on their distance from the ideal genotype. The ideal test environment should be highly discriminative of the genotypes and representative of the mega-environment (Aina *et al.*, 2007). This study showed that environment Sagure 2019(E7), Kulumsa 2020(E10), and Sagure 2020(E8) had a high discriminating ability and representativeness for the evaluation of potato varieties for MTY. The positive correlation existing between the varieties and environments indicated that these genotypes possessed a specific adaptation. The tested environment markers fall close to the bi-plot origin due to their short vectors, which means that all genotypes performed similarly in those environments. This provides little or no information about the varietal differences since the genotypes show broad adaptability. In this case, breeders find it difficult to select high-yielding and more stable potato varieties.

A closer ranking of varieties was observed for marketable tuber yield using BLUPs (Table 5 and Fig. 3d). Piepho *et al.* (2008) described that the BLUP values allow increased accuracy of the analysis to detect differences between varieties. We studied univariate stability models, the most widely used methods based on regression and variance estimates (Table 5). Based on the mean value, slope of the regression line and deviation from regression, the Gera variety was the most stable. The stability analysis is based on the variance parameters (stability indexes) i.e. the mean of the response variable (Y), best linear unbiased prediction of genotypes (BLUPg), Annicchiarico's D Parameter values (DA), Stability Measure Based on Fitted AMMI Model (FA), AMMI Stability Index (ASI), Sum Across Environments of Absolute Value of GEI Modelled by AMMI (AVAMGE), Annicchiarico's D Parameter values (DA), and Stability Measure Based on Fitted AMMI Model (FA), Gera variety was the most stable and Dagim was unstable.

Association of metric traits

The associations of metric traits combined over years and location are illustrated in Figure 5. The relationship between MTY and days required to attain 50% physiological maturity was positive but smaller in magnitude. This highlights the extended days required to mature potato varieties could improve the period between tuber bulking and the number of tubers per plant and simultaneously improve the average tuber weight (ATW). The correlation between ATW and days to maturity, marketable tuber yield, total tuber yield and plant height was strong and positive. Thus, improvement in ATW could directly improve tuber yield per unit area. However, ATW was negatively, but strongly associated with specific gravity, starch, and dry matter content. The stem number per hill was positively correlated with ATW and plant height. This association could be related to the population or stand per plot and as the number of plants per experimental plot increased the plant height and the weight of average tuber weight as the competition for resources increased. This simultaneously results in a decline in the tuber size per plant and per harvestable plot area. The present result is in agreement with the findings of Hunde *et al.* (2022), who reported a strong and positive association of tuber yield with stem height, marketable tuber yield, stem number per plant, and days to maturity. Conversely, negative associations were reported by the authors for specific gravity, days to emergency, and flowering at the genotypic level of correlation.

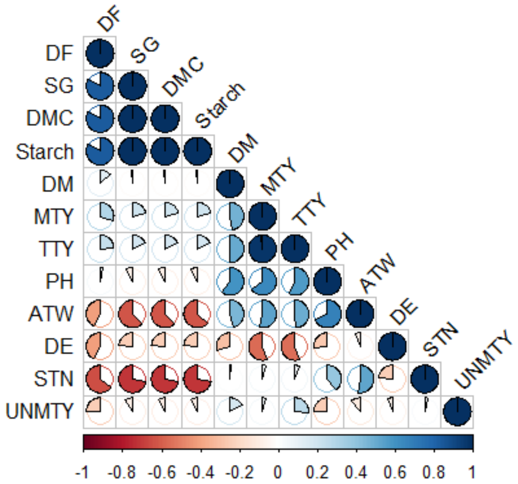


Fig. 5. Pearson correlation coefficients of phenological, agronomic, yield and related traits of 12 potato genotypes (varieties).

The relationship of specific gravity with tuber dry matter and starch contents was linear with a high coefficient of determination and strong and positive correlation. In accordance with the present result, Mohammed (2016) reported similar findings among potato varieties included in this study for those internal qualities.

Farmers' potato variety evaluation and selection

Preference traits common to each environment were selected after consulting 127 farmers, 40 at Kulumsa (5 male and 35 female), at Sagure 10 (4 men and 6 female), at Asasa 26 (19 men and 7 female), at Kofele 23 (14 male and 9 female), and at Bekoji 28 (12 men and 16 female) as 1, 2, 3, 4, and 5 represented for poor, average, good, very good, and excellent, respectively. It was possible to track each farmer's scores for every attribute.

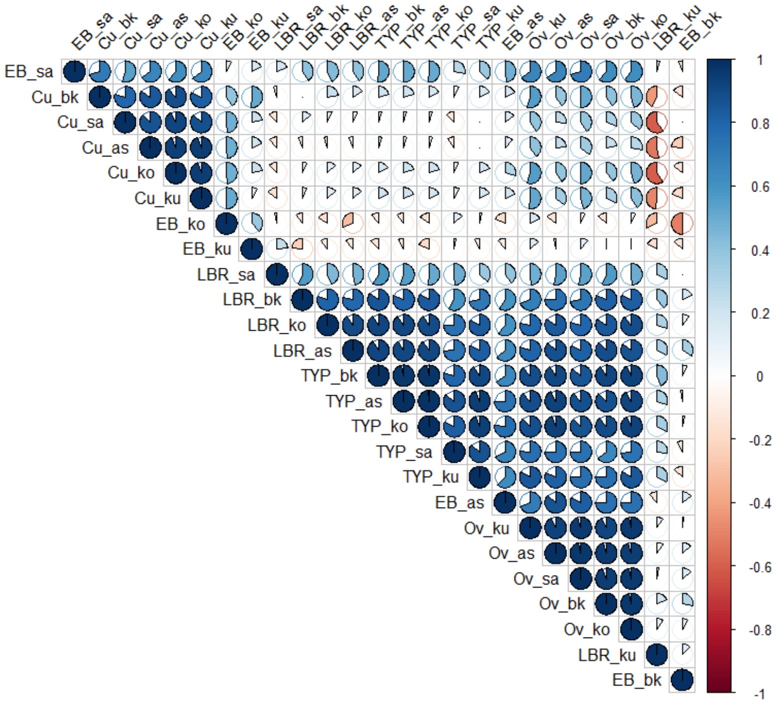


Fig. 6. Participatory evaluation scores consistent between the five environments ("bk" for Bekoji, "as" for Asasa, "ko" for Kofele, "sa" for Sagure and "ku" for Kulumsa)

An analysis of variance (ANOVA) was computed among groups for each trait based on the ratings of the chosen preference traits being significantly different. As explained by the farmers' culinary qualities, tuber yield potential and tuber characteristics are the most important determinants of marketability. Conversely, field performance (vigor), growth habit, late blight resistance, early bulking, and drought tolerance were the major determinants of the yield potential of the cultivars. The common preference traits for all the experimental locations that were used for ranking the cultivars were field performance, late blight resistance, early bulking, tuber yield potential, culinary quality, and shelf life.

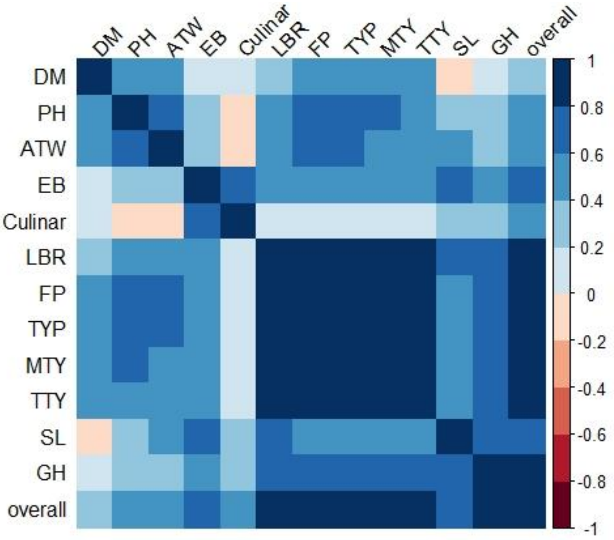


Fig. 7. CCA reporting linear combinations of agronomic and farmers' evaluations in the five environments. Abbreviations: EB= early bulking, LBR= late blight resistance, FP= field performance, TYP= tuber yield potential, SL= shelf life, GH= growth habit, Culinar= Culinary quality.

The scores of farmers for those selected traits were pseudo-normal for gender differences. The gender difference was more marked in quality and food-related traits (culinary) than in agronomic ones (field performance, early bulking). Gender-wise score correlation was lower in Sagure than in the rest of the test environments for some traits. However, the scores of the farmers were consistent, except for the tuber bulking trait, which is different from one test location to the other (Fig. 6). There were strong and positive associations between preference trait scores (Fig. 6). Conversely, the culinary quality of potato varieties was not consistent between environments.

Examining the linear combination of the metric measures of varietal performance is instrumental in understanding how the perception of variety/genotype quality by farmer communities relates to the genetic material produced by breeding (Kolech *et al.*, 2015). A canonical correlation analysis (CCA) was used to depict the best linear combinations between participatory evaluation scores and phenotypes (Fig. 7). As presented in Figure 7, there were strong and positive associations (CCA) between plant height and field performance, tuber yields potential, and in smaller magnitude for the late blight resistance and overall performance of the varieties. Strong associations with higher magnitudes of positive correlation coefficients were observed among tuber yield scores, field performance, late blight resistance, marketable tuber yield, total tuber yield, shelf life, growth habit, and overall performance of varieties (Fig. 7). In line with this, Mancini *et al.* (2016) reported similar results for 400 wheat genotypes evaluated at Hagreselam and Geregera, joining smallholder farmers' traditional knowledge with metric traits to select better varieties of Ethiopian wheat.

Conclusion

The result of this study indicated the existence of a significant ($P \leq 0.01$) difference among potato varieties. The significant effects of genotypes, locations, years and their interactions observed for the traits, justified the contribution of G×E interaction in varietal responses across test locations. This enables the identification of varieties with narrow adaptation, which can significantly improve crop productivity in specific environments. Stable and high-yielding potato varieties were identified and selected based on their relative response to a respective environment. The study sites were clustered into three separate groups for the evaluation of varieties for MTY in Southeast Ethiopia. There was score consistency between farmers of each environment and the canonical correlation between metric and metric traits was strong among some traits.

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Authors' contributions

Gizaw Wegayehu Tilahun drafted the manuscript, supervised the fieldwork and collected data, and conducted the analysis of variance, mean separation, heat map, stability analysis (AMMI, GGE, BLUP, and WAAS), CCA, and correlation**.** Nimona Fufa and Awoke Ali supervised fieldwork, collected data, and edited the manuscript with the other co-authors. Fekadu Gebretensay developed the proposal, coordinated the fieldwork, and participated in the design. Dasta Tsagaye and Demis Fikre participated in the fieldwork, designing, and reviewing of the manuscript. The final manuscript was read and approved by each contributor.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that supports the findings of this study can be made available upon reasonable request.

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