

Tuber Yield Performance and Stability of Potato Genotypes in the Potential Highlands of Ethiopia

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ABSTRACT

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Potato (*Solanum tuberosum* L.) is one of the most important and widely cultivated root and tuber crops in Ethiopia. A multi-environment national potato variety trial was conducted at Adet, Debre Birhan, Holetta, and Bekoji in Ethiopia during the 2019 and 2020 under rain-fed season to develop a high-yielding, widely adaptable, and late blight-tolerant variety with acceptable tuber quality traits. Fourteen genotypes and two standard checks, Belete and Dagim, were arranged in a randomized complete block design with three replications. Combined analysis of variance across locations and years revealed that the genotypes differed significantly in marketable and total tuber yields. The combined data also revealed that CIP-313021.31(G1) gave the highest tuber yield of 42.0 t ha⁻¹, followed by CIP-313021.4 (G11) (40.7t ha⁻¹) and CIP-313033.114 (39.4 t ha⁻¹). Similarly, AMMI and GGE bi-plot identified that G1 (CIP-313021.31) was found to be the most ideal and stable genotype with high mean tuber yield across environments. Moreover, CIP-313021.31 was selected based on a low percentage of late blight severity and has a highly farmer-preferred trait. As a result, CIP-313021.31 (G1) has been officially released and registered by the given name Tesfa for commercial production due to its high yielding, late blight tolerance, wide adaptability, and stability across environments in potato growing areas of the country.

1. INTRODUCTION

The cultivated potato (*Solanum tuberosum* L) of world importance is a clonally propagated, heterozygous autotetraploid with a chromosome number of $2n = 4x = 48$ (Spooner et al., 2014). In Ethiopia, potatoes play a crucial role in addressing food and nutrition security concerns and generating income. However, its production and productivity is highly challenged by the low productivity of local varieties, biotic and abiotic stresses, weak formal seed system, and poor farming practices (Semagn et al., 2015). Despite its importance, the productivity is low (14.2 tha^{-1}) as compared to the world average of 19.4 tha^{-1} (FAOSTAT, 2022). One of the major factors contributing to low productivity is the lack of high-yielding and late blight-resistant potato cultivars with wide adaptability and stability of performance in tuber yield. To overcome these constraints, the potato breeding program in Ethiopia has made considerable efforts. Tuber yield is a complex quantitative trait, often controlled by many genes, influenced by prevailing environmental conditions, with each gene having a small effect. Potato productivity in tuber yield is a combined result of the genotype of the variety, the environment, and the interaction between genotype and environment (Scavo et al., 2023).

Genotype-by-environment interactions (GEI) occur when phenotypes respond differently to genotypes under varying environmental conditions (Gauch and Zobel, 1996). Potato genotypes evaluated across diverse environments often display considerable yield fluctuations owing to GEI (Gedif et al., 2014; Baye et al., 2019; Scavo et al., 2023; Manamno et al., 2024). The most desirable genotype combines high yield with consistent performance across different environments and years (Piepho, 1996; Annicchiarico, 2002; Scavo et al., 2023). Interactions can be anticipated when genotypes vary in agro-morphological traits and environments differ in climatic, soil, biotic, and management factors. Kozak et al. (2011) also noted that cultivar and location main effects significantly impacted yield and traits directly influencing tuber yield.

In Ethiopia, the potato research program has assessed potato genotypes for their resistance to late blight, yield potential, and stability over the years. However, the evaluation of these new genotypes for sensory and processing qualities in the Ethiopian highlands remains unexplored. Notably, the International Potato Center (CIP) has developed potato clones with tolerance to late blight and other desirable agronomic and quality characteristics (Landeo et al., 1995). This study, therefore, was aimed at developing a high-yielding, tolerant to late blight and stable potato variety across environments. Additionally, it sought to introduce a new high-yielding potato variety that possesses suitable tuber quality traits and is acceptable to farmers.

2. MATERIALS AND METHODS

2.1. Description of Testing Sites

The national variety trial (NVT) field experiments were conducted across representative potato growing testing sites of Ethiopia, namely Adet (Northwest Ethiopia), Holetta (central Ethiopia), Bekoji (Southeast Ethiopia), and Debre Birhan (Northeast Ethiopia) in 2019 and 2020 under rain-fed conditions. The locations are the main testing sites of the national potato breeding activities *visa-à-vis* for the selection of high-yielding, late blight-tolerant, and wide-adaptable potato varieties in Ethiopia (Table 1).

Table 1. Description of the experimental sites

Location	Alt. (m.a.s.l)	Lat(N).	Long(E).	Ave.RF (mm)	Temp(°C)		Soil type
					Min	Max	
Adet	2240	11.287695	37.479477	1271	8.8	25.2	Nitosol
D/Birhan	2825	9.604608	39.499177	1260	3.0	20.0	Cambisol
Holetta	2400	9.056569	38.506100	1041.4	6.7	21.7	Nitosol
Bekoji	2780	7.544636	39.255021	1350	10.0	22.5	Nitosol

Note: m.a.s.l= meters above sea level; mm= millimeter; °C=degree celsius

2.2. Genetic Materials

Fourteen potato genotypes, along with the standard checks, were tested in the national variety trial (NVT) across testing locations for two years. The first 12 genotypes were introduced from the International Potato Center (CIP) and advanced from screening and preliminary yield trials; and rigorously evaluated and screened for table and processing purposes (Table 2). The two standard checks, Belete and Dagim, are Ethiopian varieties released and included in the trial for comparison purposes.

Table 2. List and characteristics of genetic materials tested in the national variety trial

Code ^m	Genotype	Tuber skin color	Eye depth	Tuber shape	Origin/source
G1	CIP-313021.31	light red	shallow	round-ovoid	CIP
G2	CIP-313033.114	white-cream	shallow	oblong	CIP
G3	CIP-313038.30	white-cream	shallow	ovate	CIP
G4	CIP-313033.125	dark-prple	shallow	oblong	CIP
G5	CIP-313033.139	dark-purple	shallow	ovate	CIP
G6	CIP-313021.75	red	medium	round	CIP
G7	CIP-313023.82	white-cream	shallow	oblong	CIP
G8	CIP-313021.58	purple	shallow	oblong	CIP
G9	CIP-313021.49	purple	shallow	oblong	CIP
G10	CIP-313038.3	white-cream	shallow	oblong-ovate	CIP
G11	CIP-313021.4	purple	shallow	oblong	CIP
G12	CIP-318526.2	white-cream	shallow	round	CIP
G13	Belete*	white-cream	medium	oblong	Adet ARC
G14	Dagim*	white cream	shallow	round	Adet ARC

Note: *= standard check variety; m= short code for genotype

2.3. Experimental Design and Trial Management

The experiment was laid out in a Randomized Complete Block (RCB) design with three replications. Each experimental unit consisted of 40 tubers planted in a 3m x 3m plot with an inter-row and intra-row spacing of 0.75m and 0.30m, respectively. Management of insect pests and diseases, weeding, ridging, and other cultivations were done following the recommendations of each location when required. Fertilizer was applied to each plot at a rate of 225 kg ha⁻¹ of urea and 182 kg ha⁻¹ of NPS for Adet location. Nitrogen and Phosphorus fertilizers were also applied based on the specific recommendations for the rest of the testing locations. Accordingly, 142 urea/237NPS kg ha⁻¹ for Holetta, 200 urea/150 NPS for Debre Birhan, and 165 urea/200 kg ha⁻¹ NPS for Bekoji stations were used. The whole P and S sources were applied at planting while N was split into two halves, the first half at 1st earthing-up and the remaining half at the start of flowering or the 2nd earthing-up time.

2.4. Phenotypic Trait Measurements

The data were collected uniformly across replications at each experimental site. Days to maturity (DTM) was recorded as the number of days when 50% of the plants turned into yellowish colour. Plant height (PTH) was measured in cm from the soil surface to the tip of the growing main stem when 50% of the plants matured. Harvesting was carried out once, when the plants matured, and 20 plants per plot were harvested from the central two rows and used to determine tuber traits. Tuber number plant⁻¹ (TNPP) was recorded as the number of tubers collected from a mature plant at harvest. Average tuber weight (ATW) was recorded by dividing the weight of tubers per plant by the total number of tubers per plant at harvest. Average tuber yield per plant was calculated by taking the tuber yield (fresh weight) of all harvested plants from the net plot of a cultivar, divided by the number of plants harvested. The marketable tuber yield was weighed using just commercial tubers (diameters greater than 25mm, not cracked, not diseased). The total tuber yield was the sum of marketable and unmarketable tubers (tubers less than 25mm in diameter), diseased and cracked. The tuber yield was

estimated on a plot basis, then converted to tha^{-1} . Dry matter content (DMC) is derived from the ratio of dried samples over fresh samples in grams and expressed as a percentage.

2.5. Farmer's Assessment and Sensory Evaluation

Tuber selection and boiling taste by farmers were conducted at Adet during harvesting. While the crisp quality analysis and sensory evaluation were done at the ARARI Food Science laboratory. Fresh potato tubers, which were firm, clean, wholesome, free from pests and diseases, were selected and washed. The peeled tubers were also washed thoroughly with clean water immediately to avoid colour change. It was sliced with a potato slicer and washed again to remove any residue on the surface of the sliced potato. Then dewatered using muslin cloth to reduce moisture, and easy to fry, and was fried with frying oil by using a deep frying machine at $176\text{--}180^\circ\text{C}$ till it becomes a crispy texture and light yellow in colour. Finally, it was de-oiled, cooled, and served to the panelists. Sensory evaluation of potato crisp was done using a 10-member panel as described by Larmond (1991). Sensory evaluation was conducted on colour, flavour, taste, crispiness, oiliness, and overall acceptability of the crisp. The scoring was done based on a 7-point hedonic scale where 7 = like extremely and 1 = dislike extremely.

2.6. Data Analysis

Statistical data analysis was carried out using GenStat software edition 24 (VSN international, 2024) for ANOVA and GGE bi-plot analysis. Combined analyses across locations were also performed after carrying out the homogeneity of error variance. The stability analysis of AMMI and GGE biplot was used to investigate the stability of the genotypes across testing environments. The AMMI was used to reveal the patterns of GEI as per the model described by Zobel *et.al.* (1988):

$$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^N \gamma_k \lambda_{ik} \delta_{jk} + \rho_{ij} + \varepsilon_{ij} \quad \text{Eq. 1}$$

Where: Y_{ij} is the yield of i^{th} genotype in the j^{th} environment; μ is grand mean; G_i and E_j are the genotypes and environment deviation from grand mean, respectively; λ_k is the singular value for k^{th} IPC (interaction principal component); γ_{ik} is the genotype G eigenvector (score) for k^{th} IPC axis; δ_{jk} is the environment E eigenvector (score) for k^{th} IPC axis; ρ_{ij} is the interaction residual; N is the number of principal components in the model and ε_{ij} is the random error. The GGE bi-plot analysis was carried out based on singular value decomposition (SVD) following the model developed by Yan and Tinker (2006):

$$Y_{ij} = \lambda_1 \gamma_{i1} \delta_{j1} + \lambda_2 \gamma_{i2} \delta_{j2} + \varepsilon_{ij} \quad \text{Eq. 2}$$

where, Y_{ij} is the mean of genotype i in test site j ; λ_1 and λ_2 are the SVD of the first and second principal components (PC1 and PC2), respectively, associated with the matrix of the effects of a genotype contributing to the effects of GEI; γ_{i1} and γ_{i2} are eigenvectors of the PC1 and PC2 associated with the effects of genotype i , respectively; δ_{j1} and δ_{j2} are eigenvectors of the PC1 and PC2 associated with the effects of test site j , respectively and ε_{ij} is the residual of the model associated with genotype i in the environment j .

3. RESULTS AND DISCUSSION

3.1. Analysis of Variance and Mean Performance of Tuber Yield

Combined analysis of the variance of each location over two years indicated significant ($P < 0.01$) genotypic differences for plant height, number of tubers per plant, and average tuber weight (Tables 3 and 4). Combined analysis of variance across locations and over years showed the presence of a significant ($P \leq 0.01$) difference among the tested genotypes for marketable and total tuber yields (Table 3). Similarly, the effect of $G \times L$ and $G \times L \times Y$ interactions was found to be significant ($P < 0.05$) for the most important traits of marketable and total tuber yields. Adet and Holetta are the high-yielding environments for this particular study. Accordingly, 35.85 tha^{-1} mean tuber yield was

recorded at Adet, followed by 34.8 t ha⁻¹ at Holetta. The highest tuber yield was harvested in the year 2019 (32.2 t ha⁻¹) compared to 2020 (31.97). This result indicated that 2019 was a relatively favorable season for genotypic performances.

The combined data across locations and years revealed that the highest marketable (42.1 t ha⁻¹) and total tuber yield (43 t ha⁻¹) was recorded from genotype CIP-313021.31 (G1), followed by CIP-313021.4(G11), and CIP-313033.114(G2). In contrast, the lowest marketable (15.77 t ha⁻¹) and total tuber yield (17 t ha⁻¹) was obtained from the second standard check G14 (Dagim), followed by G12 and G4 (Table 2). The new genotypes had 6.7 % to 22.9 % tuber yield advantage over G13 (Belete), and from 42.2 % to 62.4 % yield advantages over the second standard check G14 (Dagim). This is mainly attributed to the genetic difference of genotypes in yielding ability and tolerance to late blight of potato, as well as the environmental effects of testing locations.

3.2. Yield Component Traits

Combined analysis of variance over years of separate locations revealed that all the yield component traits had significant differences ($P < 0.05$) among the tested genotypes (Tables 3 and 4). Some genotypes showed better average tuber weight and tuber number per plant over the standard checks. The better mean tuber number per plant was recorded from G1 (14), followed by G2 and G3 at Adet, Holetta, Bekoji, and Debre Birhan (Tables 3 and 4). The highest average tuber weight was recorded by G2 (101.9g) at Bekoji site, whereas the lowest was recorded from G6 (41.1g) at Debre Birhan station. Generally, G1 and G2 had better average tuber weight than the rest of most genotypes across testing stations (Tables 3 and 4). Despite a comparable number of tubers per plant being recorded in all locations, a better mean tuber number per hill (12.4) was obtained at Adet site. A significant and longest maturity day was recorded by G11, followed by G10 at Adet site; while G13 and G11 had elapsed the longest days to mature (124.2 days) at Debre Birhan and Bekoji. Although most of the new genotypes have a better dry matter content (some genotypes in the acceptable ranges), they did not show a significant difference between the best standard check Belete at Adet, Holetta, and Bekoji sites (Tables 4 and 5). However, the average dry matter content ranges from 20.0 % to 23.5 %, which suggests all tested environments were ideal for good dry matter content except Debre Birhan, where DMC was not reported.

The highest and most significant AUDPC and PSI was recorded on Dagim variety in both years. A higher late blight score was recorded in 2020 than in 2019, which implies that the late blight pressure was relatively higher in 2020 than in 2019. In 2019, significantly the highest AUDPC (2622.5%) and PSI (25.46%) was recorded from variety Dagim; whereas the lowest AUDPC (64.58%) score was recorded from Belete (G13), but was not significantly different from CIP-313021.3, CIP-313038.30, CIP-313021.75, CIP-313023.82, and CIP313038.3 (Table 6). From this result, it was evident that the higher the late blight infestation, the lower the performance of the genotypes, mainly in tuber yield, in a few genotypes, such as variety Dagim.

Table 3. Mean tuber yield (tha⁻¹) potato genotypes in separate locations (Adet, DBirhan, Holetta, and Bekoji) and years (2019 and 2020)

Genotype	Adet		Holetta		Bekoji		Debre Birhan		Combined mean		MTY advantage over the checks	
	2019	2020	2019	2020	2019	2020	2019	2020	MTY	TTY	Belete (%)	Dagim (%)
CIP-313021.31	49.05	45.25	37.38	54.6	32.5	50.7	31.84	34	42.1	43.0	22.9	62.4
CIP-313033.114	39.23	40.18	43.8	38.6	24.4	35	41.76	41.2	38.02	39.4	15.1	58.5
CIP-313038.30	39.14	42.98	32.85	36.6	39.1	23.7	38.58	38.3	36.41	38.6	11.3	56.7
CIP-313033.125	28.5	31.85	34.33	38.95	23.33	13.8	33.06	14.3	27.27	29.5	-	42.2
CIP-313033.139	37.36	36.89	37.86	34.4	25.19	10.9	32.64	23.6	29.85	31.6	-	47.2
CIP-313021.75	37.37	31.11	20.65	31.7	26.67	33.02	20.47	25.4	28.30	29.2	-	44.3
CIP-313023.82	37.52	38.98	33.4	41.21	18.3	16.3	22.56	24.03	29.04	31.5	-	45
CIP-313021.58	50.29	44.4	39.96	36.9	22.5	37.7	27.86	26.2	35.72	36.9	9.6	55.4
CIP-313021.49	39.82	42.89	32.96	40.33	37.2	23.9	31.52	28.4	34.63	37.0	6.7	54.6
CIP-313038.3	47.13	46.14	32.96	50.1	28.43	21.3	32.25	32.7	36.37	39.7	11.2	56.6
CIP-313021.4	47.42	39.86	33.77	46.2	40	45.04	35.27	33.57	39.14	40.7	19.5	60.7
CIP-318526.2	12.38	16.16	29.19	18.3	22.96	48.8	25.06	12.67	23.19	26.2	-	32.5
Belete	20.42	23.92	35.47	32.8	40.8	40.7	34.98	29.2	32.28	33.7	0	51.1
Dagim	19.24	18.43	23.37	8.1	23.06	7.2	16	10.8	15.77	17.0	-	0
Grand mean	36.06	35.65	33.43	36.34	28.89	29.15	30.28	26.74	33.40	35.6		
G	**	**	*	**	*	*	*	**	**	**		
G*L									**	**		
G*L*Y									**	*		
CV (%)	18.03	16.9	16.56	13.9	30.2	18.3	18.56	34	23.5	19.8		

Note: MTY= marketable tuber yield in tha⁻¹; TTY= Total tuber yield in tha⁻¹; G=genotype effect; G*L=genotype by location interaction effect; G*L*Y=genotype-location-year interaction effect; *, **=significance level at P<0.05 and P<0.01, respectively; CV= coefficient of variation

Table 4. Yield-related traits of potato genotypes combined over years (2019-2020)

Varieties	Combined over years/ 2019-2020/					Combined over years /2019-2020 /			
	Adet					Holetta			
	DTM	PH	ATW	TNPP	DMC	DTM	ATW	TNPP	DMC
CIP-313021.31	91.17 ^{abc}	53.42 ^{bcd}	78.7 ^a	14.0 ^a	26.09 ^{ab}	103.5 ^d	84.7 ^{abc}	15.7 ^a	20.9 ^{ab}
CIP-313033.114	90.67 ^{abc}	49.39 ^d	73 ^{ab}	12 ^{abc}	22.15 ^{cde}	110.7 ^{a-d}	91.24 ^a	13.1 ^{ab}	18.8 ^{a-d}
CIP-313038.30	95.83 ^a	58.38 ^{bcd}	59.1 ^{abc}	11.6 ^{abc}	25.57 ^{ab}	109.5 ^{a-d}	68.2 ^{cd}	13.2 ^{ab}	18.2 ^{a-d}
CIP-313033.125	86.29 ^{cd}	54.73 ^{bcd}	65.8 ^{abc}	11.9 ^{abc}	21.5 ^{de}	106.7 ^{cd}	86.9 ^{abc}	10.9 ^{bc}	19.5 ^{a-d}
CIP-313033.139	84 ^d	55.04 ^{cd}	56.1 ^{abc}	11.8 ^{abc}	22.79 ^{b-e}	107 ^{cd}	78.5 ^{a-d}	11.5 ^{bc}	17.9 ^d
CIP-313021.75	91.3 ^{abc}	59.78 ^{bc}	49.4 ^{a-d}	11.3 ^{abc}	23.89 ^{a-d}	106.8 ^{cd}	73.4 ^{a-d}	10.3 ^{bc}	20.5 ^{abc}
CIP-313023.82	91.33 ^{abc}	51.61 ^{cd}	63.2 ^{abc}	8.6 ^{cd}	25.46 ^{abc}	112.5 ^{abc}	70.8 ^{bcd}	12.8 ^{ab}	21.3 ^a
CIP-313021.58	93 ^{ab}	61.96 ^b	47.3 ^{bcd}	12.4 ^{ab}	21.1 ^{de}	115.2 ^{ab}	74.2 ^{a-d}	11.1 ^{bc}	17.6 ^d
CIP-313021.49	93.83 ^{ab}	74.6 ^a	63.6 ^{abc}	8.8 ^{cd}	21.95 ^{de}	107.8 ^{bcd}	68.4 ^{cd}	10.5 ^{bc}	18.1 ^{cd}
CIP-313038.3	94.83 ^{ab}	59.25 ^{bc}	43.7 ^{bcd}	12.7 ^{ab}	26.56 ^a	115.7 ^a	77.4 ^{a-d}	12.3 ^{bc}	21.3 ^a
CIP-313021.4	95.5 ^{ab}	61.81 ^b	73.2 ^{ab}	8.3 ^{cd}	24.06 ^{a-d}	108.5 ^{a-d}	85.1 ^{abc}	10.9 ^{bc}	18.8 ^{a-d}
CIP-308526.2	83.8 ^d	53.6 ^{bcd}	52.9 ^{bc}	7.8 ^d	19.94 ^e	103.3 ^d	69.8 ^{bcd}	10.9 ^{bc}	18.6 ^{bcd}
Belete	90.33 ^{bc}	61.43 ^b	73.7 ^{ab}	9.5 ^{bcd}	25.64 ^{ab}	106.7 ^{cd}	89.2 ^{ab}	10.6 ^{bc}	20.1 ^{a-d}
Dagim	82.83 ^d	49.63 ^d	38.8 ^{cd}	7.5 ^d	22.15 ^{cde}	103.7 ^d	61.7 ^d	8.9 ^c	19.42 ^{a-d}
Mean	90.36	57.48	60	12.4	23.5	108.4	77.1	11.6	20
Sig. level	**	**	**	**	*	**	**	**	**
CV (%)	4.26	11.97	5	22.6	10.88	5.3	19.02	21.9	9.5

Note: DTM = Number of days to maturity; PH=Plant height in cm; ATW=Average tuber weight in g; TNPP= Tuber number per plant; DMC= Dry matter content in percentage; *, **=significance level at 0.05 and 0.01, respectively; CV=Coefficient of variation in %. Means followed by the same letter are not significantly different.

Table 5. Yield-related traits of potato genotypes tested over the years (2019-2020)

Varieties	Combined over years 2019-2020				Combined over years 2019-2020		
	Bekoji				Debre Birhan		
	DTM	ATW	TNPP	DMC	DTM	ATW	TNPP
CIP -313021.31	121.7 ^{ab}	90.9 ^{abc}	17.3 ^a	25.0 ^a	104.3 ^{bc}	59.6 ^{b-e}	16.2 ^a
CIP -313033.114	110.2 ^{cd}	101.9 ^a	11.8 ^{ab}	23.8 ^{ab}	102.9 ^{bcd}	74.2 ^a	12.9 ^{abc}
CIP-313038.30	118.5 ^{ab}	86.9 ^{abc}	13.8 ^{ab}	22.8 ^{ab}	108.9 ^a	50.5 ^{def}	14.1 ^{ab}
CIP-313033.125	105.3 ^d	62.6 ^d	9.3 ^{ab}	22.8 ^{ab}	97 ^{ef}	49.9 ^{ef}	11.7 ^{bcd}
CIP-313033.139	115.8 ^{bc}	84.3 ^{a-d}	8.1 ^b	21.1 ^{abc}	97.6 ^{ef}	64.7 ^{a-d}	10.2 ^{cd}
CIP-313021.75	121 ^{ab}	84.8 ^{a-d}	14.5 ^{ab}	25.5 ^a	100.2 ^{de}	41.1 ^f	14.2 ^{ab}
CIP-313023.82	115.7 ^{bc}	76.8 ^{bcd}	10.9 ^{ab}	24.7 ^{ab}	102.9 ^{bcd}	54.4 ^{def}	10.7 ^{bcd}
CIP-313021.58	105.7 ^d	71.3 ^{cd}	9.6 ^{ab}	26.0 ^a	106 ^{ab}	52.1 ^{def}	13.8 ^{abc}
CIP-313021.49	117.2 ^b	91.1 ^{abc}	10.3 ^{ab}	22.8 ^{ab}	106.8 ^{ab}	69.9 ^{ab}	8.8 ^{de}
CIP-313038.3	120.7 ^{ab}	63.1 ^d	14.9 ^{ab}	24.4 ^{ab}	106.7 ^{ab}	42 ^f	16.1 ^a
CIP-313021.4	122.2 ^{ab}	91.9 ^{abc}	17.4 ^a	24.0 ^{ab}	106.8 ^{ab}	68.8 ^{abc}	12.2 ^{bcd}
CIP-308526.2	121.2 ^{ab}	84.6 ^{a-d}	10.9 ^{ab}	26.2 ^a	101.25 ^{cd}	44.7 ^{ef}	11.4 ^{bcd}
Belete	124.8 ^a	95.7 ^{ab}	13.3 ^{ab}	25.6 ^a	105.1 ^{ab}	58.9 ^{b-e}	13.2 ^{abc}
Dagim	121.7 ^{ab}	72.6 ^{bcd}	7.8 ^c	20.3 ^b	95.3 ^f	55.1 ^{c-f}	5.8 ^e
Mean	117.3	82.7	12.1	23.5	102.9	56.1	12.23
Sig. level	**	**	*	**	**	**	**
CV (%)	4.6	20.9	5.4	19.54	15.1	21.8	21.3

Note: DTM=Number days to maturity; ATW= Average tuber weight in g; TNPP=Tuber number per plant; DMC= Dry matter content in percentage; *, **=significance level at $P<0.05$ and 0.01 , respectively; CV= Coefficient of variation in %

Table 6. Late blight response of potato genotypes

Genotype	2019		2020	
	AUDPC (%-days)	PSI (%)	AUDPC (%-days)	PSI (%)
CIP313021.31	96.67 ^{fg}	6.48 ^g	240.83 ^{fg}	9.95 ^f
CIP-313033.114	221.67 ^{def}	7.41 ^f	136.25 ^{hi}	8.10 ^h
CIP313038.30	168.75 ^{efg}	8.10 ^{ef}	192.50 ^{gh}	8.80 ^g
CIP-313033.125	1718.75 ^b	16.67 ^b	521.25 ^{ed}	12.04 ^d
CIP313033.139	351.25 ^d	8.33 ^e	585.00 ^d	12.27 ^d
CIP-313021.75	68.75 ^g	5.56 ^h	81.67 ⁱ	7.17 ⁱ
CIP313023.82	68.75 ^g	5.56 ^h	136.25 ^{hi}	8.10 ^h
CIP-313021.58	168.75 ^{efg}	8.10 ^{ef}	459.58 ^e	12.04 ^d
CIP313021.49	276.25 ^{de}	9.26 ^d	272.50 ^f	10.65 ^e
CIP313038.3	90.00 ^{fg}	6.25 ^{gh}	195.00 ^{gh}	8.80 ^g
CIP-313021.4	90.00 ^{fg}	6.25 ^{gh}	90.00 ⁱ	7.41 ⁱ
CIP-308526.2	1371.67 ^c	15.51 ^c	1696.25 ^c	19.67 ^c
Belete	64.58 ^g	5.56 ^h	210.00 ^{fg}	9.26 ^g
Dagim	2225 ^a	20.14 ^a	2622.50 ^a	25.46 ^a
Mean	498.6310	9.23	630.22	12.04
CV (%)	16.39	5.32	6.42	3.23
Significance	<.0001	<.0001	<.0001	<.0001

Note: AUDPC = Area Under Disease Progress Curve (%); PSI = percent severity index. Means followed by the same letter are not significantly different.

3.3. Farmers' preference traits and quality parameters

Involvement of farmers in varietal selection helps to overcome the shortcomings of conventional variety development approaches in several ways. It also helps to advance preferred genotypes and reject undesired ones at the right time. Farmers' participation also helps the breeders to get farmers' feedback on their desired traits and priorities (Ceccarelli, 2012). This feedback serves as input in designing appropriate breeding programs that respond to the needs and priorities of the target bio-physical and socio-economic environment. This, in turn, helps to overcome the high chance of rejection encountered when varieties are developed by researchers alone (Ceccarelli, 2012; Alemayehu et al., 2021).

In this study, farmers participated to understand the variety selection criteria and to assess their preferences. Farmers participated in the last stage or NVT of genotype evaluation so as to select their desired varieties based on their own selection criteria. Farmers first just listed the selection criteria and weighted each criterion based on the qualities each genotype has (from 1, most important trait to 6, least important trait) (Table 7). The most rated farmers' preference traits for variety selection were high tuber yield, followed by boiled taste and medium to large tuber size with shallow eye depth. Tuber skin colour was ranked as the 4th important trait. According to the farmers, white and red skin colour tubers differ in market price, i.e., white-fleshed tubers have a better price than red or pink-fleshed ones. The farmers also considered the cooking quality or elapsed time to cook and ranked it as the 6th selection criterion. Based on farmers' selection, G1, G2, and G10 ranked first, second, and third based on overall cumulative selection criteria, respectively.

When crisp quality is referenced, G2, G6, and G1 had overall acceptance by panelists based on the crisp colour, flavour, taste, crispness, and oiliness, respectively (Table 8). A potato genotype that possesses good physical quality traits like shallow eyes, round to ovoid shape, tuber uniformity, and medium tuber size is a good indication of a tuber for processing purpose and crisp preparations. Most of the tested genotypes had the above-mentioned traits (Tables 2 and 8). Hence, the current study clearly demonstrated the possibility of genotype selection for both table and processing purposes.

Table 7. Farmers' preference traits selection at Adet station (N=13 farmers)

Genotype	Considered traits by farmers						Total score	Rank
	Tuber Yield (1)	Boiled taste (2)	Tuber shape and size (3)	Skin colour (4)	Shallowness (5)	Cooking quality (6)		
CIP-313021.31	4	8	12	16	20	24	84	1 st
CIP-313033.114	4	8	12	16	17	24	81	2 nd
CIP-313038.30	3	8	9	16	20	24	80	4 th
CIP-313023.82	3	4	9	12	10	12	50	7 th
CIP-313021.58	3	4	9	12	10	6	44	8 th
CIP-313038.3	4	8	9	16	20	24	81	2 nd
CIP-313021.4	4	4	9	12	15	12	56	6 th
Belete	3	2	12	16	15	12	60	5 th

Note: Grading score: 4= very good; 3=good; 1=fair; numbers in parentheses are weighted values given for each trait by the farmers; preference rank derived from grading score and weighted value

Table 8. Result of crisp sensory evaluation of potato genotypes (panellists=10)

Genotype	Crisp color	Flavor	Crisp taste	Crispiness	Oiliness	OAA/ Mean	Preference /Rank
CIP -313021.31	4.69	4.69	4.54	6.15	5.54	5.122	3 rd
CIP -313033.114	6	5.31	5.23	6	5.69	5.646	1 st
CIP-313038.30	4.38	4.62	4.62	4.85	4.69	4.632	8 th
CIP-313033.125	3.38	3.92	3.85	3.69	3.85	3.738	13 th
CIP-313033.139	3.85	3.23	3	3.92	3.69	3.538	14 th
CIP-313021.75	6	5.38	5.08	5.15	5.31	5.384	2 nd
CIP-313023.82	4.69	4.38	4.46	6.08	5.15	4.952	6 th
CIP-313021.58	3.85	3.54	3.23	4.85	4.62	4.018	12 th
CIP-313021.49	3.69	3.77	3.69	5.92	5.38	4.49	10 th
CIP-313038.3	6	5.69	5.54	5.77	4.23	5.046	5 th
CIP-313021.4	4.85	4.69	5.31	4.77	4.65	4.854	7 th
CIP-308526.2	5.69	5.15	5.08	5.08	4.54	5.108	4 th
Belete	4.38	4.38	4.38	4.38	4.38	4.38	11 th
Dagim	5.31	4.38	4.31	5.31	3.62	4.586	9 th

Note: OAA = Overall acceptability of the crisp by panelists; Hedonic scales: 7= like extremely; 6= like very much; 5= like slightly; 4= neither like nor dislike; 3= dislike slightly; 2= dislike very much; 1= dislike extremely; scores determined by taking average values of each panelist(n=10).

3.4. AMMI Analysis for Tuber Yield

The AMMI model analysis of variance (AMMI Anova) for marketable tuber yield revealed that the genotype, environments, and genotype by environment interactions had highly significant ($P<0.001$) differences (Table 9). The first and second principal component axes were significant, and the two IPCAs together explained adequately 82.2% the genotype by environment interaction ($G \times E$) sum of squares. The first principal component axis explained 57.87% of the genotype by environment interaction ($G \times E$), and the second principal component explained 24.35% of the interaction (Table 9). The significance of the principal components ($P<0.001$) indicated that there existed a differential response of the potato clones for different environments.

Table 9. AMMI ANOVA table for tuber yield for 14 genotypes and 8 environments

Source	DF	SS	MS	V.R.	F prob.	Explained variance (%)
GENOTYPES	13	5205	400.4	6.57	<0.001	
ENVIRONMENTS	7	1387	198.2	3.17	<0.0033	
GEN*ENV	91	5405	59.4			
IPCA 1	19	3100	147.9	6.25	<0.001	57.83
IPCA 2	17	1301	75.4	3.19	<0.001	24.35
Residuals	55	1012	23.9			

Note: DF=Degrees of Freedom; SS= Sums of Squares; MS= Means of Squares; V.R= Variance Ratio

3.5. GGE Bi-plot Analysis and Stability for Tuber Yield

3.5.1. Relationships among the testing environments

The GGE bi-plot (Figure 1) generated from the environment-centered data captures 82.5% of the total variations of the GEI. The environment vectors are lines that connect the test environments to the bi-plot origin. According to Yan and Tinker (2006) and Welderufael et al. (2023) the cosine angle between the vectors indicates the correlation between the test environments. Hence, the cosine angles $<90^\circ$ (acute angle), 90° (right angle), and $>90^\circ$ (obtuse angle) of the vectors indicate positive correlations, no correlations and negative correlations between the test environments, respectively (Figure 1).

In the present study, environment AD19 had a positive correlation with HO20 but a negative correlation with BEK20. Similarly, DB19 had strong positive correlations with the environments of HO19, DB20, and BEK19. This result suggests that those three environments had similar effects on the performance of potato genotypes, and supposedly, the environments had little interaction on the GEI of potato yield. The present result is in agreement with Manamno et al. (2024), who reported that potato tuber yield was not significantly affected in these similar environments. The presence of close associations among test environments suggests that the same information about the genotypes could be obtained from fewer test environments (Yan and Tinker, 2006; Annicchiarico, 2002). On the other hand, the needs of diverse environments are imperative for future multi-environment variety evaluations to capture the genotypic performance and recommend for wide environments.

The length of an environment's vector reflects its ability to discriminate among genotypes (Yan and Tinker, 2006; Scavo et al., 2023). Longer vectors indicate greater discriminating power, while shorter vectors suggest limited ability to differentiate genotypes. For tuber yield (Figure 1), environments BEK20 and AD19 had longer vectors, indicating strong discriminating ability. In contrast, HO19 and DB20 had shorter vectors, making the environments less informative, while the other environments showed better discriminatory potential. Hence, the environments found closest to the Average Environment Coordinate (AEC) in the biplot are considered to be the most representative.

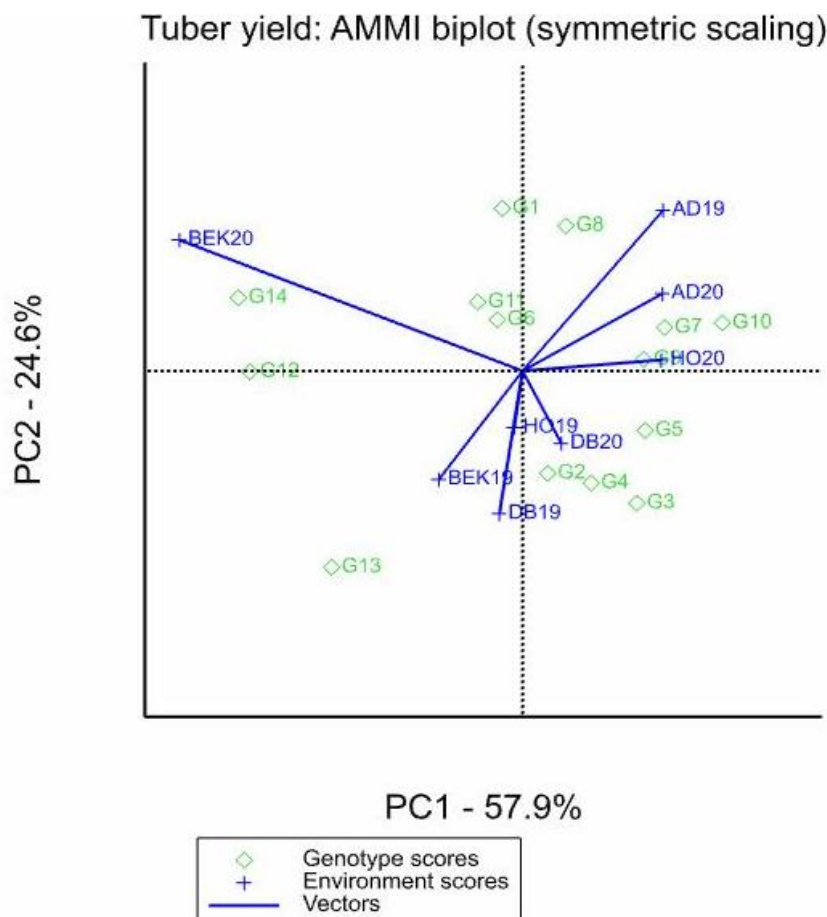


Figure 1: Environment-sector view to show relationships among test environments in discriminating the genotypes. (Note: Codes for genotypes stated in the materials and methods section; environments represented by AD19 and AD20; HO19 and HO20; DB19 and DB20; BEK19 and BEK20 stand for Adet, Holetta, Debre Birhan, and Bekoji in 2019 and 2020, respectively).

3.5.2. Which -won-where view based on GGE bi-plot

The GGE bi-plot clearly demonstrated which genotype won in which environment (Figure 2). Accordingly, the perpendicular line divides the bi-plot into 5 polygonal sectors containing the vertex

genotypes, which are displayed furthest from the bi-plot origin. Genotypes located on the vertices of the polygon performed either the best or the poorest in one or more environments (Yan and Tinker, 2006). The equality lines divide the bi-plot into sectors, and the winning genotype for each sector is the one located on the respective vertex.

In this study, all eight test environments fall into two environment groups or sectors (environment groups or sectors referring to the testing sites or environments; not mega-environment classifications). Hence, G1 was the winner genotype in most testing environments, or six environments; namely HO19, HO20, DB19, DB20, BEK19, and BEK20; whereas G10 was the winner genotype in the remaining two environments (AD19 and AD20), meaning that G10 was the best performing genotype in mid-highland environments like Adet. The genotypes that were placed within the polygon are comparatively less responsive to the environmental interaction. In this study, no environments fell into sectors with genotypes G5, G12, and G14 as the vertices, indicating that these cultivars were not paramount in any of the environments.

The polygon view of the GGE biplot for tuber yield grouped the test sites into two environment groups or sectors, with Holetta, Debre Birhan, and Bekoji included in the first environment group, while Adet was included in the second mega-environment group. The present result clearly demonstrated that there existed differential responses of potato genotypes in the mid-highland and high-altitude environments, such as Debre Birhan, Bekoji, and Holetta areas.

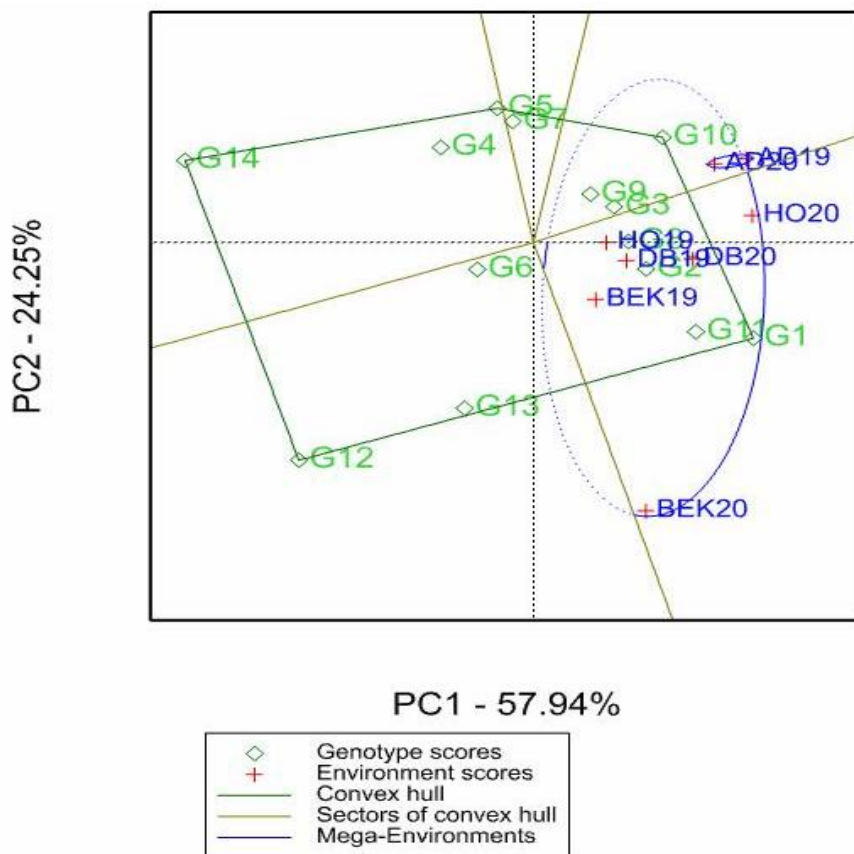


Figure 2: Polygon view of the GGE bi-plot showing the “which-won-where” view of 14 potato genotypes (G) across 8 environments.

3.5.3. Ranking of genotypes relative to the ideal genotype

The average-environment coordination (AEC) view of the GGE bi-plot is ideal for evaluating potato genotype performance and stability across test sites in this study. The average environment axis (AEA), horizontal green line, which points to genotypes with higher mean performance across testing

sites, was used to identify genotypes that are close to the ideal genotype in yield performance and stability across the test sites. In this study, G1 was at the position of the arrow of AEA on the center of the smallest concentric circle; it can be considered as an ideal genotype for tuber yield, whereas G11 and G2 were the closest to the ideal genotype, and hence these genotypes are highly desirable genotypes that perform well along with the ideal genotype across the testing environments (Figure 3). On the contrary, G14 was the poorest genotype because it consistently performed poorly across the test environments.

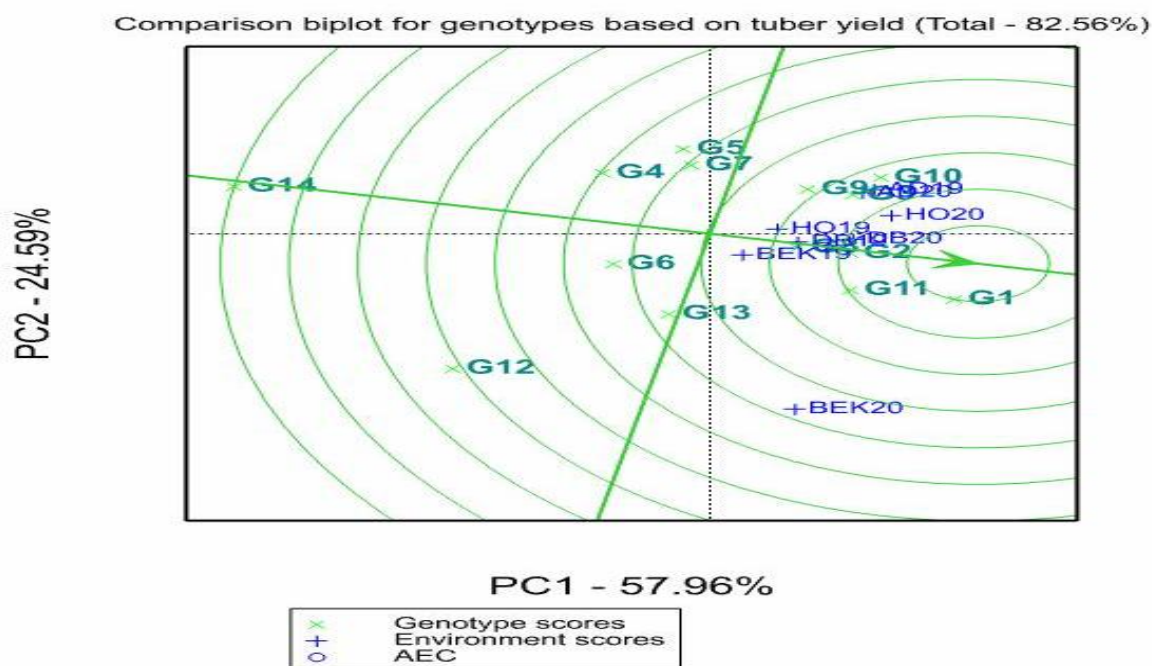


Figure 3: Ranking genotypes GGE bi-plot showing the performance of 14 potato genotypes across 8 environments in comparison to an ideal genotype

3.5.4. Ranking of genotypes based on mean yield and stability

The GGE bi-plot demonstrated that the blue horizontal line points towards the higher mean yield across environments. Thus, genotype (G1) had the highest mean yield and good stability, followed by genotypes (G2) and G11; whereas the average environment coordinate (AEC) ordinate or the blue vertical line points to greater variability (poor stability) of the genotypes in terms of tuber yield in either direction of the bi-plot (Tinker and Yan, 2006; Gedif et al., 2014). Thus, genotypes (G1 and G2) were stable genotypes, whereas G12 was highly unstable because it had a lower-than-expected yield in environments of AD19 and DB20 but a higher-than-expected yield in HO19 and BEK20 environments (Figure 4). In contrast, those genotypes with the shortest perpendicular lines (close to the average coordination axis or blue line) are considered more stable. For instance, G2 and G14 could be more stable potato genotypes, but far below in terms of tuber yield.

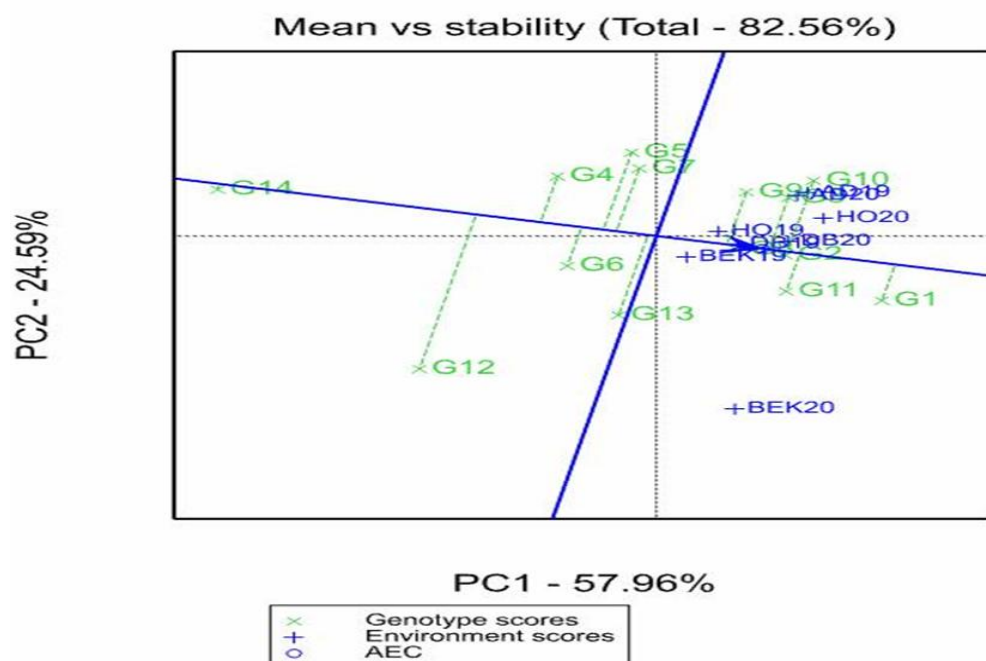


Figure 4: Ranking of genotypes based on mean tuber yield versus stability of 14 potato genotypes across 8 environments

3.6. Performance of Candidate Varieties on Variety Verification Trial

The variety verification results revealed that the first candidate variety, G1 (CIP-313021.31), had 27.9 % marketable and 25.7 % total tuber yield advantages over the recent standard check variety, Worku. Likewise, this candidate variety also had 62.5 and 60.3 % marketable and total tuber yield advantages over the second standard check variety Dagim (Table 10). The two candidate varieties, G1 and G2, had a better number of tubers per plant and average tuber weight across locations. The candidate variety (CIP-313021.31) is believed to have adult plant resistance genes or horizontal resistance, as it had consistent late blight resistance reactions and tuber yield across testing locations. Details of agromorphological traits are presented in Table 11.

Table 10. Mean performance of candidate varieties across sites during VVT in 2023

Variety	MTYtha	TTYtha	DTM	TNPP	ATW(g)
CIP-313021.31	43.0	45.78	114.33	19.24	110.54
Worku(st. ck)	31.0	33.57	110.66	16.21	83.92
CIP-313033.114	36.2	38.83	109	16.48	117.21
Dagim(st.ck)	16.12	18.18	85.5	8.872	55.33
Grand mean	31.59	34.09	104.87	15.20	91.75

Note: VVT=Variety verification trial; MTY= Marketable tuber yield in tha^{-1} ; TTY=Total tuber yield in tha^{-1} ; DTM= Number of days to maturity; TNPP=Average tuber number per plant; ATW=Average tuber weight in gram.

Table 11. Agro-morphological characteristics of the newly released variety *Tesfa* (CIP-313021.31)

Characteristic of the variety	Description
Average number of days to maturity	106
Average plant height(cm)	59.4
Growth habit	Semi-erect
Average tuber number per plant	19
Flower color	Light pink
Tuber shape	Round-Ovoid
Tuber size	Medium to large
Tuber eye depth	Shallow
Tuber skin color	Light red or dominant light red skin colour with 2 ^{ry} white cream
Tuber flesh color	White creamy
Dry matter content (%)	High (24)
Sprout shape and colour	Conical shape with pinkish sprout colour
Storage quality	Medium to long (> 90 days)
Taste	Good boiling taste and doesn't disintegrate while boiled; preferred by farmers
Crisp color	Light yellowish
Use	Ideal for fresh consumption and processing
Disease reaction	Tolerant to potato late blight disease
Marketable tuber yield(t/ha)	42.5
Total tuber yield(t/ha)	45
Recommendation domain of the variety	Northwestern highlands, Ethiopia (Adet, Debre Tabor, Dega Damot), Central highlands, Ethiopia (Holetta, D/Birhan, Mush, Ankober, Aresi/ Bekoji); and areas with similar climatic and edaphic factors of the country.
Year of release	2024
Breeder/maintainer of the variety	Adet Agri.Res.Center/ARARI

4. CONCLUSION AND RECOMMENDATIONS

To set a new genotype for variety development and release, the genotypic performance and its interaction with the environment should be assessed across diverse locations and years. For this reason, the present research was conducted to evaluate the performance of potato genotypes across locations and over years in the Ethiopian highlands. Potato genotypes that are evaluated in different environments encounter considerable environmental fluctuations in yield performance as a result of genotype-by-environment interaction. The GGE bi-plot analysis identified the stable and unstable genotypes based on tuber yield data. Hence, the new genotype CIP-313021.31(G1) was the most stable with a high tuber yield, followed by CIP-313033.114 (G2) and G11. These candidate varieties had good tuber shape, size, boiling taste, as well as good crisp quality. Hence, the two candidates (G1 and G2) were verified across 12 sites for potential release in 2023 under rain-fed conditions. The candidate varieties were also visited by the NVR technical committee. In this study, assessment of farmers indicated that a good genotype should possess high yield, good boiling taste, and medium to large size, shallow eyes, tuber skin colour, and cooking quality (elapsed time to cook). Based on farmers' selection, G1, G2, and G10 ranked first, second, and third based on overall cumulative selection criteria, respectively. Therefore, CIP-313021.31 has been officially released and registered by the given name *Tesfa* for commercial production. The new variety *Tesfa* is believed to boost production and productivity and largely benefit our potato-growing farmers in the near future. Therefore, *Tesfa* has been recommended for production for its wide adaptability and stability across environments for the potential potato-growing areas of the country.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request

Conflict of interest statement

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

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