



Development of a Potato Variety Derived from Local Crosses for Off-Season Irrigated Production in Ethiopia

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ABSTRACT

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Potato (*Solanum tuberosum* L.) is a key food and cash crop in Ethiopia, and its production in the off-season under irrigation conditions is rapidly expanding. However, all nationally released potato varieties have been developed primarily for rainfed production systems, resulting in poor adaptation and low productivity in off-season under irrigation. This study aimed to develop and identify a high-yielding, stable, and widely adapted potato variety for off-season potato production under irrigation using locally developed crosses. A total of 1,700 genotypes derived from local crosses were progressively evaluated and selected in the off-season production under irrigation. Nine elite genotypes, along with three check varieties, were evaluated across six mid-highland environments in 2022 and 2023 off-season periods using an irrigation supplement. A randomized complete block design with three replications was used. Data on phenology, agronomic traits, tuber yield, and quality parameters were taken and analyzed using combined ANOVA and GGE biplot methods. Significant effects of genotype, environment, and their interactions were observed for most yield and quality traits, indicating substantial genetic variability and strong genotype × environment interaction. Genotype AD5016170.6 consistently outperformed all checks, recording the highest tuber yield (34.21 t ha⁻¹), along with superior dry matter, starch content, and specific gravity. GGE biplot analysis and stability indices further confirmed AD5016170.6 as the most stable and broadly adapted genotype across environments in the off-season under irrigation. This candidate genotype exhibited yield advantages of 37–77% over check varieties. The study demonstrates that irrigation-specific breeding for off-season production using local crosses can substantially enhance potato productivity. Genotype AD5016170.6 was recommended for national variety verification and officially released on 11 May 2026, for off-season potato production under irrigation conditions in Ethiopia. The variety, locally named Mesno-1, was the first potato variety developed through crossing and selection specifically for off-season potato production under irrigation in Ethiopia.

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) is a major food and cash crop in Ethiopia, playing a vital role in food security, household income, and nutrition, particularly in the mid- to high-altitude agro-ecologies. In recent years, potato production has expanded considerably, driven by improved production technologies and the increasing use of irrigation agriculture in the off-season (Abebe et al., 2021). The crop is cultivated under both rainfed and irrigation systems; however, despite substantial differences in temperature regimes, soil moisture availability, and disease pressure between these systems, farmers commonly grow the same potato varieties across seasons.

To date, all nationally released potato varieties in Ethiopia have been selected and evaluated primarily under rainfed production conditions, with no varieties specifically bred or officially released for off-season (November–April) production systems under irrigation (Yigzaw et al., 2008; Abebe et al., 2020; Abebe et al., 2021). As a result, farmers rely on varieties that are poorly adapted to off-season production, exposing crops to heat stress or high temperature and frost risk. Nationally, potato is predominantly cultivated during the *Belg* (short rainy) season, which accounts for approximately 57% of the total potato-growing area, followed by off-season production under irrigation (25%) and the *Meher* (main rainy) season (18%). Similarly, the Belg season accounts for the largest proportion of total potato production (53%), followed by off-season production under irrigation (27%) and the Meher season (20%). Notably, the area cultivated on off-season under irrigation and its contribution to total production exceed those of the Meher season by 38.8% and 35%, respectively (Tadesse et al., 2025).

The increasing shift from Meher-season to off-season potato production under irrigation is largely driven by farmers' efforts to escape high disease late blight pressure during the main rainy season, which often results in substantial yield losses and increased production costs due to frequent fungicide applications (Gebeyehu et al., 2024). In Ethiopia's northwestern, central, and eastern highlands, potato production in the off-season under irrigation accounts for a large share of the national potato area; however, productivity remains significantly lower than that achieved under rainfed conditions (CSA, 2019/2020). Previous studies in Ethiopia have demonstrated significant genotype $\times$ environment interactions between rainfed and off-season production systems under irrigation, indicating differential varietal responses across environments (Baye et al., 2022; Yigzaw et al., 2008; Abebe et al., 2020). Consistent with this, studies conducted in subtropical countries such as India and the United States have reported wide genetic variation in potato performance under warm conditions in the off-season (Bhagsari et al., 1988). These findings underscore the necessity of developing potato varieties for off-season production by irrigation to fully exploit the production potential of potato farming while enhancing climate resilience.

Therefore, the present study aimed to develop a potato variety adapted to off-season production systems under irrigation conditions in Ethiopia using breeding populations derived from conventional crosses by Adet Agriculture Research Center. The breeding program was designed to select genotypes with early maturity, high tuber yield, rapid bulking rate, wide adaptation to off-season production environments, and market-preferred tuber quality traits under supplemental irrigation.

2. MATERIALS AND METHODS

2.1. Experimental Sites

Potato field experiment was conducted in different areas of Ethiopia, at Adet (Koga site), Holeta Agricultural Research Center station, Wondo Genet Agricultural Research Center station, Fogera Rice Research and Training Center, Rib irrigation site, and Finote Selam sub-center Gary irrigation site in Ethiopia during 2022 and 2023 in the off- season under irrigation (Table 1). Based on the Ethiopian agro-ecological zone classification, all sites are located in the mid-highland agroecological belts.

Table 1. Description of the study area

Locations	Altitude (masl)	Soil type	Max annual mean temperatures		Average annual rainfall
			Max	Min	
Adet ARC (Koga irrigation site)	1875	Vertisol	26.8 °C	9.7 °C	1430.9 mm
Holetta ARC station	2400	Nitisol	22°C	6°C	1100 mm
Fogera ARC (Rib irrigation site)	1774	Fluvisols	27.7°C	14.0°C	1216.3mm
Finote Selam Sub Center (Gary site)	1790	Vertisols	30°C	11°C	1400mm
Wondogenet ARC site	1876	sandy loam	26.72°C	12.02°C	1372 mm

Note: ARC = Agricultural Research Center, Max=maximum, Min = minimum. The Koga and Rib irrigation sites were described by Alebachew E. et al. (2020), Dires Tewabe et al. (2021), and Belachew Muche Mekonen (2025); the Wondo Genet ARC irrigation site by Damtew Abewoy et al. (2022); and the Holetta ARC station by Adina et al. (2019) and the official EIAR Holetta Agricultural Research Center website. (eiar.gov.et)

2.2. Plant Materials

A total of 1,700 genotypes were developed through conventional crossing at the crossing blocks of Adet Agriculture Research Center in Ethiopia. After early-generation screening in the off-season under irrigation conditions, 60 genotypes were selected and advanced to preliminary yield trials. Finally, nine elite genotypes, together with three check varieties, were evaluated across locations. There is no potato variety released for off-season under irrigation conditions in the country. Hence, the three commonly growing potato varieties in off-season by irrigation supplement were used as standard checks for comparisons. Ater Ababa, a farmer's variety widely grown in northwestern Ethiopia in the off-season under irrigation; Gudene, a variety widely grown in all parts of the country and reported to perform well in the off-season under irrigation (Abebe et al., 2021); and Belete, a high-yielding rainy-season variety, were evaluated across multiple locations in the national variety trial system (Table 2).

Table 2. Genotypes evaluated in the national variety trial in the off-season under irrigation at five locations in 2022 and 2023

No	Genotype code	Pedigree
G1	AD501613.100	CIP-396031.118 x Granola
G2	AD5015606.5	Belete x Ater Ababa
G3	AD5016170.22	Belete x Granola
G4	AD5016170.6	Belete x Granola
G5	AD5016161.38	CIP-395077.12 x Granola
G6	AD5016170.79	Belete x Granola
G7	AD501662.12	Gudene x Granola
G8	AD5016606.164	Belete x Ater Ababa
G9	AD501632.14	Dagim x CIP-395077.12
G10	Ater Ababa	Standard Check 2
G11	Gudene	Standard Check1
G12	Belete	Standard Check 3

2.3. Experimental Design and Management

A randomized complete block design (RCBD) with three replications was used at all experimental sites. Each plot consisted of four rows, each measuring 3m in length, with inter-row and intra-row spacing of 75 cm and 30 cm, respectively. Irrigation was applied once per week using the recommended furrow irrigation method at all experimental sites. Fertilizer rates varied by location based on site recommendations: at Koga, 180 kg NPS and 117 kg Urea ha⁻¹ were applied; at Holeta, 236 kg NPS and 165 kg Urea ha⁻¹; at Wondo Genet, 236 kg NPS and 142 kg Urea ha⁻¹; at Finote Selam sub center (Gary site), 180 kg NPS and 117 kg Urea ha⁻¹; and at Fogera Rib irrigation site, 180 kg NPS and 176 kg Urea

ha⁻¹. Recommended agronomic and weed management practices were uniformly implemented at the appropriate crop growth stages throughout the growing season.

2.4. Data Collection

In the national variety trial on off-season, data were collected from plants grown in the two central rows of each plot to minimize border effects. The recorded traits included days to maturity (DMA), plant height (PH), number of main stems per plant (NSP), number of tubers per plant (NTP), average tuber weight (ATW), marketable tuber yield (MTY), unmarketable tuber yield (UNMY), total tuber yield (TTY), tuber dry matter content (DM%), tuber starch content (SC%), and tuber specific gravity (SG). At harvest, tubers were classified into marketable and unmarketable categories. Unmarketable tubers comprised very small, malformed, and cracked tubers, whereas marketable tubers included healthy tubers with a diameter greater than 20 mm. Total tuber yield was computed as the sum of marketable and unmarketable tuber yields.

To determine tuber dry matter and starch content, a representative sample of 200 g of marketable tubers per genotype was collected from each site and replication. The samples were washed, oven-dried to a constant weight, and weighed to estimate dry matter content. Total starch content (%) was estimated from tuber dry matter percentage following the AOAC (1980) method using the equation: Starch (%) = 17.55 + 0.891 × (Tuber dry matter (%) - 24.182). Tuber-specific gravity was determined using the weight-in-air and weight-in-water method described by Kleinkopf and Wassermann (1987). A five-kilogram sample of tubers was weighed in air and subsequently weighed while submerged in water. Specific gravity (g/cm³) was calculated using the following formula:

$$\text{Specific gravity} = \frac{\text{Weight in air}}{\text{Weight in air} - \text{Weight in water}} \quad \text{Eq. 1}$$

2.5. Data Analysis

The collected data were subjected to analysis of variance (ANOVA) using R software version 4.5.2. Mean comparisons among genotypes were performed using the Least Significant Difference (LSD) test at the 5% probability level.

The superiority of the candidate potato genotype for off-season production under irrigation was evaluated based on tuber yield performance relative to standard check varieties. Yield advantage was expressed as the percentage increase in tuber yield of the candidate genotype compared with the improved standard check (Gudene), the local standard check (Ater Ababa), and the widely grown rainy-season improved variety (Belete). Yield advantage was calculated using the following formula:

$$\text{Yield Advantage (\%)} = \left(\frac{\text{Yield of Test Genotype} - \text{Yield of Standard Check}}{\text{Yield of Standard Check}} \right) \times 100 \quad \text{Eq. 2}$$

Genotype-by-environment interaction and yield stability were further assessed using GGE biplot analysis. Stability analysis was conducted using four stability parameters: AMMI Stability Index (ASI), AMMI Stability Value (ASV), Harmonic Mean of Genotypic Values (HMGV), and Harmonic Mean of Relative Performance of Genotypic Values (HMRPGV). The ASI and ASV were computed using the *Metan* R package following the procedures described by Jambhulkar et al. (2017) and Purchase (1997), respectively. The HMGV and HMRPGV indices were estimated based on BLUP values derived from mixed-effect models according to Colombari Filho et al. (2013) using the *Metan* R package (Olivoto & Lúcio, 2020). Lower ASI and ASV values indicate greater genotype stability, whereas higher HMGV and HMRPGV values indicate superior and stable performance across environments.

Environmental indices (EI) were calculated to classify test environments as favorable or unfavorable. The environmental index for each environment was computed as the difference between the mean yield of all genotypes in a given environment and the grand mean yield across environments. Environments with positive EI values (EI > 0) were considered favorable, whereas those with negative EI values (EI

< 0) were considered unfavorable, following the methods of Finlay and Wilkinson (1963) and Eberhart and Russell (1966).

3. RESULTS AND DISCUSSION

3.1. Yield Performance of Potato Genotypes in the off-season Under Irrigation

The multi-location evaluation of nine potato genotypes and three varieties in the off-season under irrigation conditions at Koga, Rib, Wondogent, Holeta, and Gary sites during the 2022 and 2023 seasons revealed significant variation among genotypes for most agronomic, yield, and quality traits (Tables 3-7). The combined analysis of variance at Koga showed that genotype effects were significant for all measured traits, indicating substantial genetic variability among the tested potato genotypes in the off-season under irrigation conditions (Table 3). Highly significant ($P \leq 0.001$) differences were observed for plant height, number of stems per plant, number of tubers per plant, marketable tuber yield, and total tuber yield, while days to maturity, average tuber weight, unmarketable tuber yield, dry matter content, starch content, and specific gravity were significant at $P \leq 0.05$. Moreover, the genotype $\times$ year interaction was significant for all traits, suggesting that genotype performance varied across the two growing seasons. Similar findings have been reported in potato, where seasonal environmental variation significantly affects the expression of yield and quality traits, emphasizing the importance of multi-year evaluation before variety release (Yan & Kang, 2003; Acquaaah, 2012).

Among the evaluated genotypes, AD5016170.6 exhibited superior performance, recording the highest total tuber yield (34.20 t ha^{-1}) and marketable tuber yield (31.07 t ha^{-1}) at the Koga irrigation site, significantly outperforming all the check varieties. At the Rib irrigation site, AD5016170.6 again performed best, with a total tuber yield of 43.9 t ha^{-1} , while AD501613.100 and AD5016170.22 also produced comparatively high yields. The greater productivity observed at the Rib irrigation site is likely associated with more favorable growing conditions, including adequate soil moisture, moderate temperatures, and suitable soil characteristics during the cropping season. These findings indicate the broad adaptation and high yield potential of AD5016170.6 in the off-season irrigated production systems in northwestern Ethiopia.

At Wondo Genet, genotype AD5016170.6 again outperformed the other genotypes with 37.0 t ha^{-1} total tuber yield, followed by AD501632.14 and Belete (Table 5). In addition, the highest number of main stems, average tuber weight, marketable tuber yield, and tuber quality traits were collected from genotype AD5016170.6. The moderate climatic conditions may have favored tuber initiation and bulking, since potato tuber formation is highly promoted by cool night temperatures that enhance assimilate translocation and dry matter accumulation in tubers (Levy & Veilleux, 2007; Hancock et al., 2014). Furthermore, the genotype expressed the highest dry matter content, starch content, and specific gravity.

Likewise, at the Holeta ARC irrigation site, AD5016170.6 recorded the highest marketable yield, total tuber yield (41.9 t ha^{-1}), and tuber quality traits, demonstrating strong adaptability on cool highland off-season under irrigation conditions (Table 6). The high yield obtained at Holeta could be related to the cool temperature, which is favorable for potato tuberization and assimilate partitioning to tubers (Hancock et al., 2014). Belete and AD5016170.79 also showed relatively good performance at this site.

In contrast, the Finote Selam (Gary) site recorded the lowest tuber yields from all genotypes among all testing sites (Table 7). The maximum total tuber yield at this site was only 16.51 t ha^{-1} from genotype AD501632.14, while genotype AD5016170.6 produced 14.07 t ha^{-1} . The reduced productivity at Gary site is mainly associated with high temperature stress during the off-season irrigation production period. Potato is a cool-season crop, and elevated temperatures adversely affect tuber initiation, tuber bulking, and assimilate translocation to underground parts. High temperature also accelerates plant respiration and vegetative growth at the expense of tuber formation, resulting in reduced marketable and total tuber yields (Milan et al., 2022).

The combined analysis of variance revealed that genotype (G), environment (E), and their interaction (G $\times$ E) significantly influenced marketable and total tuber yield, tuber number per plant, plant height, dry matter, starch content, and specific gravity ($P \leq 0.05$ – 0.001). These results indicate substantial

genetic variability and pronounced G×E interaction, underscoring the need to select genotypes specifically adapted to off-season under irrigation production systems. This finding aligns with previous Ethiopian and global reports demonstrating that potato genotypes respond differently in the off-season under irrigation versus rainfed production systems, attributable to variations in temperature, soil moisture, and disease pressure (Yigzaw et al., 2008; Bhagsari et al., 1988; Abebe et al., 2020, 2021).

In the present study, genotype AD5016170.6 (G4) recorded the highest combined mean values for agronomic and tuber yield traits across environments, outperforming all other test genotypes and check varieties. This genotype also exhibited superior quality attributes, higher dry matter (25.11%), starch content, and specific gravity, combined with medium eye depth, and good tuber shape and storage quality, indicating suitability for both table and processing uses. Potato varieties with tuber dry matter of 18–20% are considered suitable for table purposes (boiling/baking), whereas those with dry matter above 20% are recommended for processing into chips, French fries, and flakes (Souza and Silva, 2003). Higher tuber dry matter is directly linked to improved nutritional value and processing quality in potatoes (Kaur et al., 2025). Furthermore, the tuber yield of AD5016170.6 (G4) exceeded yields reported for the Ethiopian varieties Gudene, Belete, Guassa, and Jalene in the off-season under irrigation production conditions (Abebe et al., 2020; Mohammed et al., 2025).

Table 3. Combined mean performances of genotypes in different traits at Koga site in the off-season under irrigation (2022 and 2023)

Trt	Genotype	DMA	Ph	NSP	NTP	ATW	MTY	UNMY	TTY	DM	SC%	SG
1	AD501613.100	99.3b	43.2cd	3bc	7.5bc	65.4b	18.25cd	1.5ab	19.79cde	25.0abc	18.32abc	1.09cde
2	AD5015606.5	104ab	48.7c	3bc	8bc	58.3b	17.95cd	2ab	19.9cde	25.8ab	19ab	1.098ab
3	AD5016170.22	106ab	41.1d	3bc	8bc	62.2b	20.9c	1.7ab	22.6bcd	25.1abc	18.4abc	1.093bcd
4	AD5016170.6	102b	60.3b	4a	11.1a	86a	31.07a	3.1a	34.2a	25.3abc	18.55abc	1.10a
5	AD5016161.38	112a	48.8c	2cde	8.7abc	65.7b	21.9bc	1.4b	23.26bcd	23.9 ^{a-d}	17.37a-d	1.087edf
6	AD5016170.79	105ab	61ab	3bc	10.9a	62.6b	27.1ab	1.2b	28.28b	25.1abc	18.35abc	1.09cde
7	AD501662.12	103b	60b	2cde	6.5c	61.2b	16.45cd	1.2b	17.6cde	23.3bcd	16.78bcd	1.09cde
8	AD5016606.164	108ab	48.8c	2cde	8bc	62.1b	17.95cd	2ab	19.96cde	26.4a	19.56a	1.097ab
9	AD501632.14	102b	48.9c	3bc	10.4ab	53.9b	20.22cd	1.9ab	22.13b-e	22.28d	15.86d	1.083f
10	Ater Ababa	100b	43.9cd	3bc	10.6a	57b	21.1c	2.7ab	23.83bc	24.1a-d	17.51a-d	1.092bcd
11	Gudene	103b	61.8ab	3bc	7.4c	57.4b	15.9cd	1.1b	17.1de	22.78cd	16.3cd	1.086ef
12	Belete	100b	67.3a	2cde	6.4c	66.5b	14.2d	1.5ab	15.74e	25.67ab	18.87ab	1.095abc
	Mean	103.9	52.23	3	8.71	63.05	20.51	1.793	22.3	24.53	17.86	1.092
	Genotype	*	***	***	***	**	***	*	***	*	*	*
	Year*genotype	*	**	***	***	*	***	*	***	*	*	*
	Year*Location	*	**	**	***	ns	***	***	***	***	***	**
	CV	6.22	10	18.8	21.7	16.2	21.8	63.4	20.8	7.9	9.7	0.97

Note: Trt=treatment *** = very highly significant at $P \leq 0.001$, ** = highly significant at $P \leq 0.01$, * = significant at $P \leq 0.05$, DMA=days to maturity, Ph = plant height, NSP = Number of stems per plant, NTP=Number of tubers per plant, ATW=average tuber weight(g), MTY=marketable tuber yield($t\ ha^{-1}$), UNMY=unmarketable tuber yield($t\ ha^{-1}$), TTY=total tuber yield($t\ ha^{-1}$), DM=dry matter content(%), SC=tuber starch content(%), SG = specific gravity($g\ cm^{-3}$)

Table 4. Mean performance of genotypes in different traits at Fogera rib site in the off-season under irrigation (2022)

Trt	Genotype	DMA	Ph	NSP	NTP	ATW	MTY	UNM	TTY	DM%	SC%	SG
1	AD501613.100	113ab	74.33ab	4abc	15a	96abc	45.97a	2.17bcd	48.14a	25.7abc	18.9abc	1.103ac
2	AD5015606.5	106ab	57.73c	3cde	5c	70ef	11.8d	1.17cde	12.97e	26.9a	19.96a	1.108a
3	AD5016170.22	112ab	74.8ab	4bcd	10abc	109a	40.43a	2.7bcd	43.13ab	25.8abc	19abc	1.103ac
4	AD5016170.6	117a	78a	4bcd	11abc	105ab	42.14a	1.76cde	43.9ab	26.3ab	19.4ab	1.105ab
5	AD5016161.38	107ab	60.87c	3cde	7bc	88cd	28.69b	0.78e	29.47c	22.1de	15.7de	1.087de
6	AD5016170.79	101b	75.67ab	4bcd	11abc	92bcd	29.43b	4.27a	33.7bc	23.9bcd	17.3bcd	1.094bcd
7	AD501662.12	114ab	65.2bc	3cde	10abc	66ef	22.81bc	1.09e	23.9cde	25.1abc	18.4abc	1.1abc
8	AD5016606.164	109ab	77ab	5a	10abc	65f	23.9bc	1.1cde	25cd	25.8abc	19abc	1.103abc
9	AD501632.14	108ab	56.2c	3de	9abc	60f	15.3cd	1.6cde	16.9de	20.4e	14.1e	1.078e
10	Ater Ababa	114ab	66.8abc	5a	11abc	59f	21.38bc	1.52cde	22.9cde	24.2a-d	17.6a-d	1.096a-d
11	Gudene	117a	78.20a	5a	9abc	80de	24.88b	1.12de	26cd	23.4cd	16.9cd	1.092cd
	Mean	111	69.53	4	10	80.7	27.9	1.7	29.6	24.5	17.9	1.097
	CV%	6.23	9	14	27.6	9.8	17.7	30.9	20.3	5.9	7.2	0.6
	Significance	*	**	**	*	***	***	*	***	**	**	**

Table 5. Mean performance of genotypes in different traits at Wondogent in the off-season under irrigation (2023)

Trt	Genotype	DMA	Ph	NSP	NTP	ATW	MTY	UNM	TTY	DM%	SC%	SG
1	AD501613.100	98.3a-d	58.2f	5.1a	4f	72.2e	9.0g	2.4ab	11.4e	18.4g	12.4g	1.07f
2	AD5015606.5	101.7ab	60e	4.7a	7cd	92.8a-d	22.8cd	2.5ab	25.3b	21.5b	15.2b	1.084b
3	AD5016170.22	98.3a-d	62.4d	4.6a	2g	78.1cde	4.9h	2.7ab	7.6f	17.5h	11.6h	1.065g
4	AD5016170.6	91.7cde	75.3b	4.2a	9b	107.8a	35.2a	1.8b	37.0a	23.2a	16.7a	1.092a
5	AD5016161.38	103.3a	60.5e	4.5a	7cd	73.8e	18.9de	1.8b	20.7c	18.5g	12.5g	1.07f
6	AD5016170.79	96.7a-e	74.9b	4.9a	8bc	85.8b-e	24.1c	1.7b	25.8b	19.8e	13.7e	1.076d
7	AD501662.12	90de	71.8c	5.1a	5e	81.4cde	16.2ef	1.9b	18.1cd	18.8fg	12.7fg	1.071ef
8	AD5016606.164	96.7a-e	71.9c	4.3a	5e	76.6de	12.7gf	2.5ab	15.2d	19.2ef	13.2ef	1.073e
9	AD501632.14	88.3e	73.9b	4.4a	10a	85.7b-e	32.9ab	2.3ab	35.3a	21.1bc	14.8bc	1.082bc
10	Ater Ababa	93.3b-e	63.8d	4.8a	7cd	101ab	22.4cd	3.4a	25.8b	20.8cd	14.5cd	1.08c
11	Gudene	95a-e	63d	4.3a	7cd	93.4abc	22.8cd	1.6b	24.4b	19.8e	13.7e	1.076d
12	Belete	100abc	77.4a	4.6a	9b	99.3ab	31.1b	3.5a	34.1a	20.5d	14.3d	1.079c
	Mean	96.1	67.8	4.63	7	87.4	21.1	2.3	23.38	19.9	13.76	1.076
	CV%	5.6	1.6	16.6	9.5	11.3	10.95	28.7	9.2	1.85	2.39	0.157
	Significance	*	***	ns	***	**	***	ns	***	***	***	***

Table 6. Mean performance of genotypes in different traits at Holetta in the off-season under irrigation (2022)

Trt	Genotype	Ph	NSP	NTP	ATW	MKY	UNM	TTY	DM%	SC%	SG
1	AD501613.100	51.58bc	3.66a	10.3ab	70.2bcd	29.2abc	3.46bc	32.66abc	22.8bc	16.32bc	1.09bc
2	AD5015606.5	48.58c	2.67bc	8.0b	70.6bcd	16.91d	6.34abc	23.25c	24.93ab	18.22ab	1.099ab
3	AD5016170.22	53.7bc	3.33ab	11.0ab	68.9bcd	31.2ab	3.01bc	34.21abc	22.27bc	15.84bc	1.087bc
4	AD5016170.6	60.17ab	3.33ab	11.3ab	84.47ab	36.63a	5.27bc	41.9a	25.87a	19.05a	1.104a
5	AD5016161.38	51.58bc	3.0abc	8.3b	90.0a	31.57ab	1.11c	32.68abc	22.4bc	15.96bc	1.088bc
6	AD5016170.79	63.63a	3.3abc	10.0ab	77.1abc	32.98ab	2.47c	35.45ab	21.1c	14.77c	1.082c
7	AD501662.12	52.08bc	2.67bc	9.0b	67.7bcd	25.2bcd	1.92c	27.1bc	23.87ab	17.27ab	1.094ab
8	AD5016606.164	47.25c	3.67a	9.0b	72.7abc	23.7bcd	6.48abc	30.18bc	24.53ab	17.86ab	1.097ab
9	AD501632.14	46.04c	2.67bc	9.0b	66.2bcd	18.16d	6.91abc	25.07bc	20.8c	14.54c	1.08c
10	Ater Ababa	52.08bc	3.67a	13.0a	53.37d	20.06cd	10.84a	30.9abc	22.8bc	16.32bc	1.09bc
11	Gudene	51.46bc	3.3ab	9.0b	64.27cd	15.73d	8.25ab	23.98c	21.1c	14.77c	1.08c
	Mean	52.56	3	10	71.41	23.93	1.75	30.67	22.95	16.45	1.090
	CV%	9.8	17.9	22.5	15.7	23.36	29.88	21.73	7.06	8.78	0.67
	Sig	*	*	*	*	*	*	*	*	*	*

Table 7. Mean performance of genotypes in different traits at Finote Selam Gary site in the off-season under irrigation (2022)

Trt	Genotype	DMA	Ph	NSP	NTP	ATW	MKY	UNM	TTY	DM%	SC%	SG
1	AD501613.100	98.3ab	53.3a	1.7a	5.7c	32.3cd	5.7def	0.5bc	6.17cde	20.67c	14.42c	1.08c
2	AD5015606.5	95ab	63.0a	2.3a	4.3c	28.3d	5.1def	0.6bc	5.38de	22.33abc	15.9abc	1.087abc
3	AD5016170.22	95ab	60.3a	2.0a	4.3c	39.67	5.6def	0.4bc	6.04dce	25.67a	18.87a	1.102a
4	AD5016170.6	96.7ab	56.0a	1.7a	6.0ab	55.9ab	13.2ab	0.9b	14.07a	24.67ab	17.98ab	1.098ab
5	AD5016161.38	101a	55.5a	2.3a	5.7c	38.47cd	8.8cd	0.6bc	9.37bc	22.5abc	16.05abc	1.088abc
6	AD5016170.79	96.7ab	66.0a	2.3a	10.3a	33.6cd	11.5bc	1.5a	13.0ab	22.67abc	16.2abc	1.088abc
7	AD501662.12	93ab	58.0a	2.0a	3.3c	39.cd	2.7f	0.6bc	3.28e	22.5abc	16.05abc	1.088abc
8	AD5016606.164	100a	70.5a	2.3a	4.3c	44.7bc	7.4de	0.5bc	7.85cd	23.83abc	17.24abc	1.094abc
9	AD501632.14	88.3b	54.6a	2.3a	11.0a	41.1bcd	15.8a	0.7bc	16.51a	21.5bc	15.16bc	1.083bc
10	Ater Ababa	96.7ab	52.9a	2.0a	3.3c	41.5bcd	4.6ef	0.7bc	5.33de	23.83abc	17.24abc	1.094abc
11	Gudene	96.7ab	63.7a	1.7a	3.3c	59.1a	6.9de	0.1c	6.98cd	21.67bc	15.31bc	1.084bc
	Mean	96.11	60.56	2.02	5.27	41.49	7.88	0.67	8.53	23.14	16.62	1.091
	CV%	6.89	20.49	36.08	27	19.57	27.87	56	25.12	9.34	11.5	0.9
	Sig	*	ns	ns	*	***	***	*	***	*	*	*

Table 8. Combined mean of genotypes in different traits across environments in the off-season under irrigation (2022 and 2023)

Trt	Genotype	DMA	Ph	NSP	NTP	ATW	MTY	UNM	TTY	DM%	SC%	SG
1	AD501613.100	101 ^{abc}	54.8 ^d	3.3 ^{ab}	8.1 ^{bc}	66.98 ^b	21.05 ^c	1.94 ^b	22.99 ^c	22.9 ^{cde}	16 ^{cde}	1.09 ^{cde}
2	AD5015606.5	102 ^{abc}	54.5 ^d	3.1 ^a	6.7 ^{cd}	62.97 ^b	15.42 ^f	2.4 ^b	17.86 ^e	24.6 ^{ab}	17.9 ^{ab}	1.098 ^{ab}
3	AD5016170.22	103 ^{ab}	55.6 ^d	3.4 ^{ab}	7.3 ^{cd}	69.98 ^b	20.64 ^{cd}	2.0 ^b	22.7 ^{cd}	23.58 ^{bc}	17 ^b	1.093 ^{bcd}
4	AD5016170.6	99.8 ^{abc}	65 ^{bc}	3.5 ^a	9.9 ^a	87.3 ^{ab}	31.22 ^a	2.99 ^{ab}	34.21 ^a	25.11 ^a	18.38 ^a	1.100 ^a
5	AD5016161.38	104 ^{abc}	54.3 ^d	2.9 ^{bc}	7.6 ^{cd}	118.9 ^a	20.3 ^{cde}	2.8 ^{ab}	23.13 ^c	22.3 ^{def}	15.8 ^{edf}	1.087 ^{edf}
6	AD5016170.79	101 ^{abc}	67 ^{ab}	3.3 ^{ab}	10.2 ^a	69.0 ^b	25.35 ^b	2.1 ^b	27.4 ^b	22.9 ^{cde}	16 ^{cde}	1.09 ^{cde}
7	AD501662.12	101 ^{abc}	61.2 ^c	2.9 ^{bc}	6.7 ^{cd}	62.7 ^b	15.62 ^f	2.3 ^b	17.94 ^e	22.8 ^{cde}	16 ^{cde}	1.09 ^{cde}
8	AD5016606.164	103 ^{ab}	60.7 ^c	3.2 ^{ab}	7.6 ^{cd}	63.8 ^b	17.24 ^{ef}	2.5 ^b	20 ^{cde}	24.4 ^{ab}	17.7 ^{ab}	1.097 ^{ab}
9	AD501632.14	97.3 ^c	54.8 ^d	3.0 ^{abc}	9.8 ^a	60.1 ^b	20.44 ^{cd}	2.6 ^{ab}	23.0 ^c	21.4 ^f	15.1 ^f	1.083 ^f
10	Ater Ababa	101 ^{abc}	53.9 ^d	3.5 ^a	9.1 ^{ab}	61.5 ^b	18.5 ^{c-f}	3.7 ^a	22.1 ^{cd}	23 ^{bcd}	17 ^{bcd}	1.092 ^{bcd}
11	Gudene	102 ^{abc}	63 ^{bc}	3.3 ^{ab}	7.0 ^{cd}	68.5 ^b	17.02 ^{ef}	2.2 ^b	19.3 ^{de}	21.9 ^{ef}	15.53 ^{ef}	1.086 ^{ef}
12	Belete	98.3 ^{bc}	70.9 ^a	2.56 ^c	6.0 ^d	70.15 ^b	22.65 ^c	2.5 ^b	24.92 ^c	24 ^{abc}	17 ^{abc}	1.095 ^{abc}
	Mean	101.12	59.19	3.21	8.11	71.9	20.13	2.47	22.6	23.23	16.71	1.092
	CV	6.25	11.5	19.7	25.1	86	20.66	63.18	20.55	7.29	9.03	0.71
	Genotype(G)	ns	***	*	***	ns	***	*	***	**	***	***
	Environment(E)	**	***	***	***	**	***	**	***	**	***	***
	G x E	***	***	***	ns	ns	***	**	***	**	***	***

Note: DMA=days to maturity, Ph = plant height (cm), NSP = Number of stems per plant, NTP=Number of tubers per plant, ATW=average tuber weight, MTY=marketable tuber yield, UNMY=unmarketable tuber yield, TTY=total tuber yield, DM=dry matter content (%),SC%=tuber starch content, SG = specific gravity, *** = very highly significant at $P \leq 0.001$, ** = highly significant at $P \leq 0.01$, * = significant at $P \leq 0.05$, ns = non-significant, G x E=genotype by environment locations

3.2. Tuber Yield Advantages of Candidate Genotype over Standard Check Varieties

When come to tuber yield advantage over checks, the candidate potato genotype AD5016170.6 exhibited a marked yield advantage over both improved and local standard check varieties (Table 9). The yield advantage was calculated as the percentage increase in tuber yield of the test genotype relative to each standard check. The candidate genotype AD5016170.6 outperformed the improved standard check Gudene variety by 77.25%, indicating a substantial yield improvement in the off-season under irrigation. Similarly, AD5016170.6 recorded a 54.8% yield advantage over the local check Ater Ababa variety, demonstrating its superior productivity compared with farmers' commonly grown varieties under irrigation in the off-season. Compared with the widely cultivated rainy-season improved variety Belete, the candidate genotype exhibited a 37.27% yield advantage. The consistently higher tuber yield advantage of AD5016170.6 over both improved and local checks in the off-season under irrigated conditions highlights its strong yield potential and adaptability, suggesting its suitability for further verification and possible release for irrigated potato production systems in the off-season.

The yield of G4 substantially exceeds the national average (3.7 t ha^{-1}) for irrigated potatoes in off-season and the mean yield (13.9 t ha^{-1}) of rainfed varieties, representing a clear genetic gain (Abebe et al., 2024). Moreover, G4 outperformed yields reported in previous off-season irrigation multi-location trials in Ethiopia, including the highest yield of 30.08 t ha^{-1} reported by Abebe et al. (2024), as well as those reported by Misgina (2016) and Yigzaw et al. (2008). These results demonstrate tangible progress in breeding for off-season irrigation-specific adaptation.

Table 9. Tuber yield advantage over checks

No	Genotype code	Description	Tuber yield advantage%
1	AD5016170.6	Candidate genotype	
2	Gudene	Standard check 1 improved variety	77.25
3	Ater Ababa	Standard check 2 local variety	54.8
4	Belete	Standard check 3 improved variety	37.27

3.3. Genotype × Environment Interaction and Yield Stability

The GGE biplot analysis effectively captured the combined effects of genotype (G) and genotype × environment interaction (GEI) for total tuber yield in the off- season under irrigation. The first two principal components explained 52.57% (PC1) and 37.38% (PC2) of the total GGE variation, accounting for 89.95% of the total variation (Fig 1-3). This high explanatory power indicates that the biplot provided a reliable summary of genotype performance and environmental differentiation, and clearly demonstrates the presence of differential genotype responses across environments in the off-season under irrigation (Yan & Kang, 2003; Yan & Tinker, 2006).

3.3.1. Ranking of genotypes relative to the ideal genotype

According to Yan and Kang (2003), the ideal genotype is the one that yields the highest and is positioned at the center of the concentric circles and somewhat closer to the AEA arrowhead. The ranking view of the GGE biplot (Figure 1) identified AD5016170.6 (G4) as the ideal genotype, as it was positioned closest to the center of the concentric circles, indicating the combination of the highest mean total tuber yield and superior yield stability. G4 consistently ranked above the average environment axis and showed minimal deviation from the stability axis, confirming its broad adaptation to off-season under irrigation. In contrast, the standard checks Ater Ababa (G10) and Gudene (G11) were located farther from the ideal genotype position, reflecting both lower yield potential and reduced yield stability.

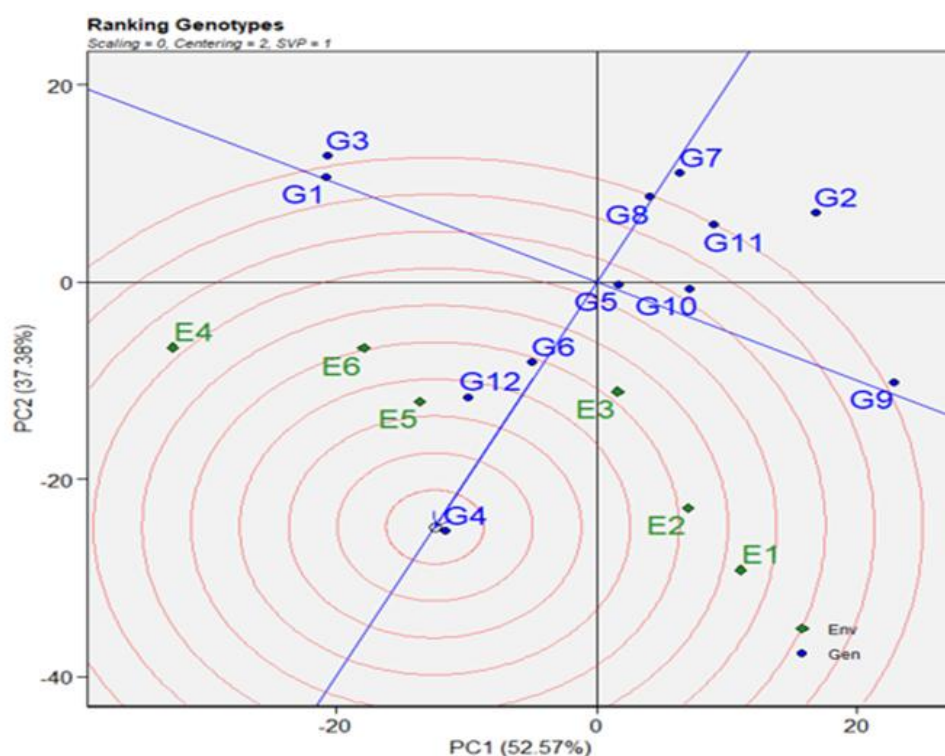


Figure 1: Ranking of 12 genotypes for tuber yield in six environments on off-season under irrigation

Note: E1= Wondo Genet, E2=Koga year 1, E3=Finote salem, E4=Fogera rib, E5=Holeta, E6=Koga year 2

3.3.2. Which-won-where pattern and mega-environment delineation

The GGE biplots, which-won-where polygon view, is the most effective method for showing genotype patterns, winning genotypes, environmental interactions, and mega environments (Yan and Rajcan 2002). The “which-won-where” view of the GGE biplot (Figure 2) identified two distinct mega-environments among the test sites, indicating the presence of crossover genotype $\times$ environment interaction. The first mega-environment consisted solely of E4, where genotype G1 occupied a vertex position and emerged as nearly the winning genotype, reflecting its specific adaptation to this environment. The second mega-environment included E1, E2, E3, E5, and E6, within which genotype AD5016170.6 (G4) was positioned at the vertex and consistently outperformed the other genotypes, indicating its broad adaptation and superior performance across diverse environments in the off-season under irrigation.

The clustering of E1, E2, E3, E5, and E6 within the same sector suggests similar genotype response patterns and a shared winning genotype (G4), despite variation in their mean yields. Although E3 exhibited a relatively low average tuber yield compared to the other environments, it was still grouped within this mega-environment because GGE biplot classification is based on genotype performance patterns rather than absolute yield levels. Environments located within the same sector are characterized by a similar ranking of genotypes and a common winning genotype (Yan et al., 2000; Yan & Kang, 2002). In addition, E3 was positioned close to the origin, indicating a weak contribution to genotype discrimination and a low ability to differentiate among genotypes. According to Yan and Rajcan (2002), environments with shorter vectors are less effective for selecting superior genotypes, whereas those farther from the origin provide greater discriminatory power and are more informative for genotype evaluation.

In the polygon view of the GGE biplot (Figure 2), G1, G2, G3, G4, G7, and G9 were identified as vertex genotypes due to their positions farthest from the origin. Vertex genotypes represent either the best or

poorest performers in specific environments, depending on sector location (Mehari et al., 2015). Among them, only G4 was associated with sectors containing test environments and is therefore identified as winning genotype in its respective mega-environment. In contrast, the sectors corresponding to G2, G3, G7, and G9 did not contain any test environments, indicating that these genotypes were not the highest-yielding in any of the evaluated locations.

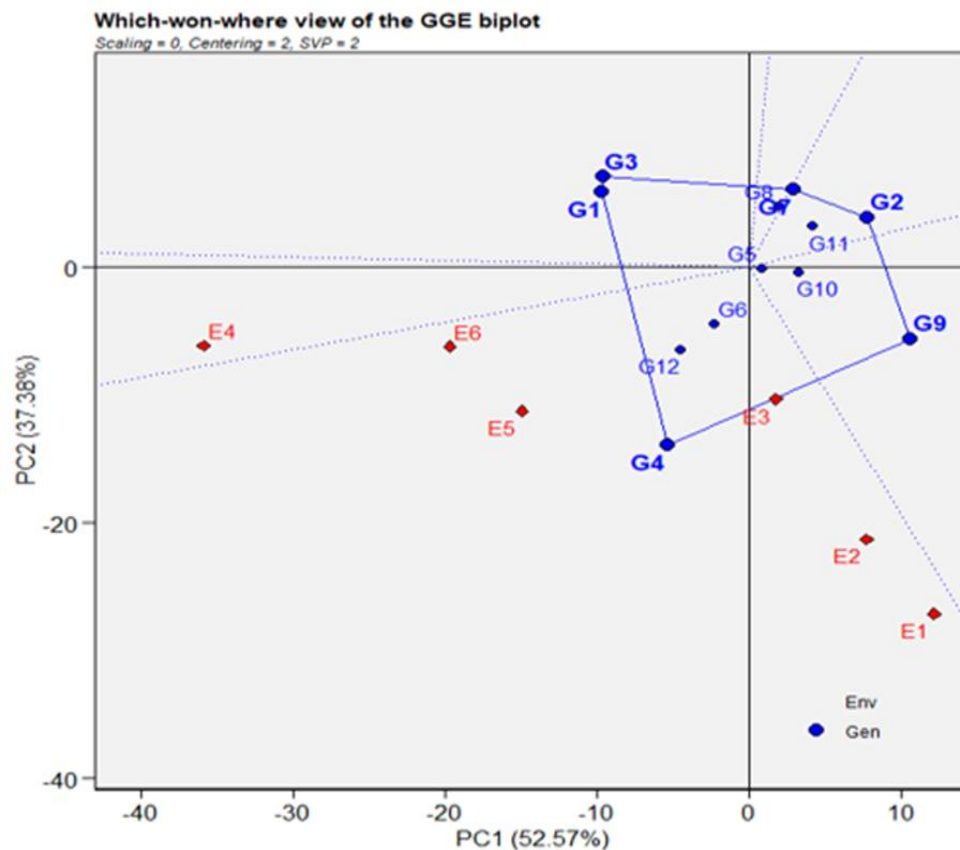


Figure 2: The polygon (which-won-where) view of the GGE biplot

Note: E1= Wondo Genet, E2=Koga year 1, E3=Finote salem, E4=Fogera rib, E5=Holeta, E6=Koga year 2

3.3.4. Mean performance and yield stability of genotypes

The mean versus stability view of the GGE biplot (Figure 3) revealed substantial differences among potato genotypes in both yield performance and stability across environments in the off-season. Genotype AD5016170.6 (G4) combined above-average mean yield with relatively high stability, as indicated by its favorable position near the average environment coordination (AEC) abscissa and its relatively short projection onto the AEC ordinate. This suggests that G4 had consistent performance across environments and possessed wide adaptation in the off-season irrigation conditions. Similar findings were reported by Yan and Kang (2003), who indicated that genotypes located closer to the AEC abscissa with shorter projections are considered more stable and widely adapted across environments.

Genotypes G2 and G9 exhibited relatively high mean yields but had longer projections onto the AEC ordinate, indicating considerable yield fluctuation and lower stability across test environments. Such instability suggests that these genotypes were highly responsive to specific environmental conditions and may possess specific rather than broad adaptation. According to GGE biplot interpretation principles, genotypes with large deviations from the AEC axis tend to interact strongly with

environments, resulting in inconsistent performance across locations and seasons (Yan et al., 2000; Yan & Tinker, 2006).

In contrast, check varieties such as Ater Ababa (G10) and Gudene (G11) were positioned close to the origin with relatively low mean yield and poor stability, indicating limited adaptation and lower productivity under irrigated conditions in the off-season. Belete (G12) displayed moderate yield performance but comparatively lower stability, suggesting that although it performs reasonably well in some environments, its response was inconsistent across locations. The observed variation among genotypes further confirms the presence of strong genotype $\times$ environment interaction, emphasizing the importance of multi-environment testing for identifying stable and high-yielding potato varieties adapted to off-season under irrigation production systems in Ethiopia (Yigzaw et al., 2008; Abebe et al., 2020).

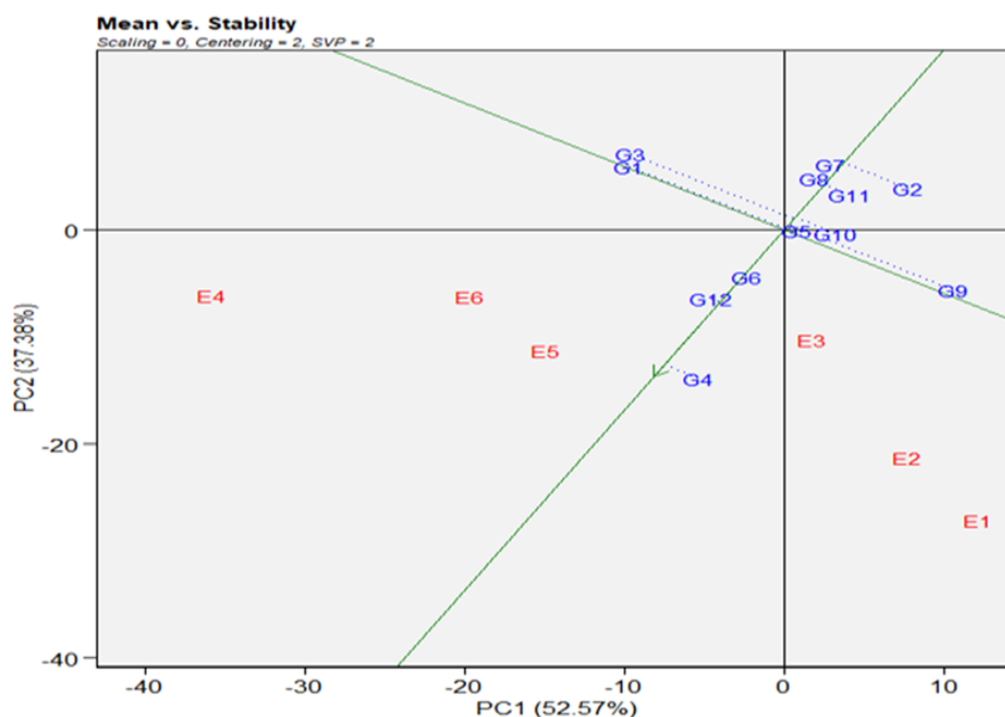


Figure 3: The mean vs. stability view of the GGE biplot

Stability indices (Table 10) strongly supported the biplot interpretation. G4 recorded the lowest ASI (0.09) and ASV (1.07), together with the highest HMGV (29.17), RPGV (1.51), and HMRPGV (1.50), indicating superior yield stability and broad adaptability under off-season irrigation conditions. Similarly, G6 also showed favorable stability combined with relatively high tuber yield, suggesting good adaptation across environments. In contrast, G2 and G9 exhibited higher instability despite their comparatively good mean yields, indicating specific adaptation rather than wide adaptability. These findings are consistent with previous reports in potato, where stability indices and GGE biplot analyses have effectively identified stable and high-yielding genotypes across environments, emphasizing the importance of using multi-trait stability approaches in genotype selection (Yan & Kang, 2003; Mohammadi et al., 2010).

Mean total tuber yield and environmental indices further classified Holetta (30.67 t ha⁻¹) and Rib Fogera (29.64 t ha⁻¹) as highly favorable environments with strong positive indices. Koga year 2 (28.23 t ha⁻¹) was also favorable, whereas Koga year 1 (16.87 t ha⁻¹) and Finote Selam Gary site (8.54 t ha⁻¹) were classified as unfavorable environments, likely due to heat stress effects that reduced yield potential and resulted in negative environmental indices. Wondo Genet, despite moderate productivity (23.38 t ha⁻¹), showed strong discriminating ability, making it useful for identifying specifically adapted genotypes. Similar patterns have been reported in potato and other crops, where environment-specific yield

differences are strongly influenced by temperature and moisture variation, and favorable environments tend to enhance genotype expression while stress environments reduce performance (Yan & Kang, 2003; Acquaaah, 2012; Gauch, 2013). These findings highlight the importance of multi-location testing under irrigation in the off-season environments to identify genotypes that combine high yield with stability. The superior stability performance of G4 and G6 further supports the effectiveness of locally developed crosses in producing well-adapted potato genotypes for off-season irrigated production systems.

Table 10. Stability indices and classification of test environments based on total tuber yield

No	GEN	Yield	ASI	ASV	HMGV	RPGV	HMRPGV	env	Yield	index	Condition
1	G1	22.99	2.81	32.15	13.97	0.93	0.8	E1	23.38	0.49	favorable
2	G2	17.86	1.45	16.56	13.63	0.79	0.74	E2	16.87	-6.02	unfavorable
3	G3	22.68	2.9	33.17	13.21	0.91	0.75	E3	8.54	-14.4	unfavorable
4	G4	34.21	0.09	1.07	29.17	1.51	1.5	E4	29.64	6.75	favorable
5	G5	23.13	0.23	2.59	19.5	1.03	1.02	E5	30.67	7.78	favorable
6	G6	27.41	0.09	1.03	23.85	1.23	1.21	E6	28.23	5.34	favorable
7	G7	17.94	0.1	1.1	11.23	0.75	0.7				
8	G8	19.69	0.12	1.35	16.17	0.87	0.86				
9	G9	23	3.01	34.4	21.52	1.15	0.97				
10	G10	22.09	0.79	9.09	15.93	0.95	0.92				
11	G11	19.25	0.65	7.4	15.51	0.85	0.84				
12	G12	24.92	0.51	5.8	14.17	1.11	1.08				

Note: E1= Wondo Genet, E2=Koga year 1, E3=Finote salem, E4=Fogera, E5=Holetta, E6=Koga year 2, GEN=genotype, ASI=Ami stability index, ASV= AMMI Stability Value, HMGV= Harmonic Mean of Genotypic Values, RPGV =Relative Performance of Genotypic Values

Table 11. Description of Meson-1 variety developed for off-season under irrigation production

1	Local name of variety	Mesno -1 variety
2	Year of crossing	2016
3	Pedigree	Belete x Granola
4	Genotype code	AD5016170.6
5	Type of mating	Bi parental
6	Plant height	Medium height with intermediate type of stem
7	Foliage	Medium-sized leaf with light green coloration
8	Flower color	White
9	Growth habit	Some erect
10	Days to maturity	99.8
11	Yield (t ha ⁻¹) on research sites	14.07-43.9
Tuber characteristics		
	Tuber skin color	White
	Eye depth	Medium
	Shape	Round- oval
	Flesh color	White
	Sprout	Strong and medium-sized
	Tuber storage life	Has long storage quality

4. CONCLUSION AND RECOMMENDATION

The multi-location evaluation of potato genotypes under off-season irrigation conditions revealed significant genetic variability and highly significant genotype × environment interactions for tuber

yield, yield-related, and quality traits. This indicates that genotype performance varies considerably across environments in the off-season under irrigation and confirms that selection under rainfed conditions alone is inadequate for improving productivity under irrigation during the off-season. Therefore, targeted breeding and evaluation for off-season production systems under irrigation are essential. Among the tested genotypes, AD5016170.6 showed consistently superior performance across environments. It recorded the highest marketable and total tuber yield, higher average tuber weight, and desirable quality traits, including high dry matter content, starch content, and specific gravity. Stability analysis further confirmed that this genotype combined high yield potential with broad adaptation and stable performance under irrigated conditions in the off-season. The observed yield advantage over standard and local checks demonstrates the effectiveness of potato breeding efforts for off-season production systems under irrigation in Ethiopia. Following multi-stage evaluation, AD5016170.6 was advanced to national variety verification trials and subsequently approved by the National Variety Releasing Committee. It was officially released on 11 May 2026 with the local variety name “Mesno-1” for off-season potato production under irrigation in Ethiopia.

The study did not assess physiological traits related to heat tolerance and processing quality attributes, such as reducing sugar content and suitability for chip and French fry processing. In addition, apart from bacterial wilt, no major disease pressure was observed during the study period, which may limit the comprehensive evaluation of genotype performance under diverse biotic stress conditions. Future research should include evaluation of physiological and all processing quality traits, particularly under frost and heat stress and disease-prone environments, to ensure more comprehensive characterization of genotypes. Furthermore, large-scale disease-free early generation seed multiplication, on-farm demonstration trials, and improved agronomic management practices, including optimized fertilizer rates and planting dates, should be strengthened to maximize the yield potential and adaptability of Mesno-1 across diverse agro-ecologies for off-season production systems under irrigation.

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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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