

Evaluation of Newly Introduced Durum Wheat Genotypes for Performance and Resilience in Algerian Semi-Arid Climate

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Abstract: In Algeria, durum wheat is the main cereal staple crop, cultivated on most of the agricultural land in use. This research investigates the performance of ten durum wheat genotypes under rainfed conditions of a semi-arid environment in Algeria over three growing seasons (2020-2023). The methodology involves monitoring phenomorphological traits, yield-related components and assessing yield stability. The genotypes, included three Algerian cultivars, used as check plant material, alongside genotypes from with Italy, Turkey, Tunisia and ICARDA. The experiment was conducted as part of the international PRIMA project "IMPRESA", aimed at improving resilience to abiotic stresses in durum wheat. Results highlighted significant effect of seasonal variability on all yield components, genotypic differences between local and introduced material and the influence of heading earliness stage. Notable interactions were observed between season and genotype, as well as between seasonal heading earliness. Introduced genotypes showed the highest grain yield across seasons, with Saragolla reaching 2.75t ha⁻¹. However, Icaerverve, and Dorato showed high yield-stability performance across seasons. In contrast, the introduced genotype Margherita showed the highest instability with values of 15 and 0.7 for Kang's rank-sum and Wricke's ecovalence indices, respectively. Over all the results indicated that Algerian genotypes have lower performances compared to the introduced genotypes, these findings offer valuable insights for future genotype screening strategies using the tested plant material.

Keywords: *Wheat, Yield Components, Genotype x Environment Interaction, Stability, Semi-arid, Algeria.*

Introduction

Durum wheat (*Triticum durum* Desf.) production in Algeria holds a crucial position within the agricultural landscape, serving as one of the most important cultivated crops. As a staple food for the population, wheat bears a significant portion of the dietary needs, and its cultivation engages a large segment of the agrarian community. In the context of socioeconomic insights, durum wheat represents a cornerstone for food security and economic stability. Cereal production occupies approximately 80% of the country's utilized agricultural area (UAA). The area sown annually with cereals is between 3 and 3.5 million

hectares, together durum and barley represent almost 85 percent of the planted area devoted to cereals (USDA, 2024). Wheat consumption in the country exceeds 10.5 Mt, for a production that fluctuates on average between 2 and 3 million tons (Bouchafaa et al., 2023). The country relies heavily on wheat imports, the quantities of imported wheat were multiplied by more than 20 between 1961 and 2023 from 442,000 tons to 9.4 million tons (USDA, 2025), with wheat import frequently exceed 5-6 million tonnes annually, representing a significant economic challenge. Garoui and Aissani (2024) noted that wheat is a staple crop in the Algerian diet, but the country remains far from auto-sufficiency due to urbanization of agricultural land, Kouri (2017) estimated that Algeria will continue to import wheat because domestic production is still mostly weather driven, highlighting the critical need for production enhancement. Climate change has dramatically intensified environmental pressures, Sahnoune et al. (2013) noted significant yield reductions due to increasing temperature variability and prolonged drought periods. The semi-arid regions in Algeria are characterized by limited rainfall and unpredictable climate conditions. Research conducted on Water productivity by Zaïm et al. (2024) under Mediterranean climates in Morocco, Lebanon and Jordan, indicates that genotype selection plays a critical role in boosting durum wheat performance under stress conditions. Several studies in similar landscape demonstrated that certain durum wheat genotypes exhibited superior drought resilience, and maintaining yield stability despite variations in precipitation (Bassi and Sanchez-Garcia, 2017). Physiological Traits such as chlorophyll content, membrane stability index, and relative water content are crucial under drought conditions (Chaya et al., 2025).

These insights underline the necessity for localized assessments of newly introduced genotypes to identify those best suited to Algeria's semi-arid climate. Fellahi et al. (2013) demonstrated the importance of developing drought-tolerant wheat varieties specifically adapted to the environmental conditions in Algeria. The study underlined that genetic improvement is crucial for enhancing wheat productivity in water-stressed environments. These findings provide valuable insights that can be adopted and implemented in similar semi-arid regions across North Africa, particularly in Tunisia and Morocco, where comparable water-limited conditions and climatic constraints create analogous challenges for wheat production systems. Furthermore, the socioeconomic implications extend beyond agricultural productivity, as improved wheat productivity could enhance food security and strengthen rural livelihoods in regions where wheat serves as both a staple crop and primary income source for smallholder farmers.

The work aims to assess climate-resilience durum wheat genotypes by using the agronomic traits and yield stability, also, the study focuses on the effect of (i) genotype, (ii) heading earliness stage and (iii) season as the main factors of variability, as well their interactions. The genotypes set is obtained from the plant material of PRIMA-funded project, assessed under Algerian high plateaus semi-arid climate and compared to Algerian genotypes over three seasons. The experimentation timespan covered different climate patterns, with favourable climatic conditions in 2021-2022, and harsher climatic conditions in 2022-23. Indeed, the integration of new durum wheat genotypes into the local farming system can potentially enhance productivity and economic viability of Algerian farms, especially in light of increasing climatic variability. As agriculture remains the backbone of many rural communities in Algeria, advancing the breeding of climate-resilient wheat varieties is critical for food security and development.

Materials and Methods

Experimental conditions and plant material

This research was conducted at the experimental farm of the University Ferhat ABBAS-Sétif1, of an area of 1.3ha (Elevation 1084 m.a.s.l, latitude 36°11' N, and longitude 5° 22' E), representing a typical semi-arid environment with an average annual rainfall of 385 mm. The soil is slightly alkaline with pH of 7.88, the electrical conductivity is recorded at 432.83 $\mu\text{S}/\text{cm}$, presenting suitable soil conditions for cereal growth. The levels of nutrients are 50.57 mg/kg for nitrogen, 162.86 mg/kg for phosphorus, and 158 mg/kg for potassium, which represents a satisfactory nutritional balance to support good plant growth. The study was carried out across three seasons spanning 2020 to 2023. In this study, ten durum wheat genotypes were obtained from the plant material provided by the international PRIMA project conducted between 2019 and 2023 entitled: *Improving resilience to abiotic stresses in durum wheat: enhancing knowledge by genetic, physiological and “omics” approaches and increasing Mediterranean germplasm biodiversity by crop wild relatives-based introgressiomics “IMPRESA”*. The set of genotypes used in the field experiment included: 1- Icaverve: an early-heading and a disease resistant genotype, 2- Minosse; known by its adaptability, high quality and early heading, 3- Margherita: with early heading stage, foliar disease resistance and yield stability, 4- Om Rabia: an early heading genotype, recognized as a drought-resistant and high-yielding genotype, 5- Saragolla: a Syngenta cultivar, breed in 2004, known by biotic and abiotic stress resistance, high grain yield and quality, 6- Sorgul, a Turkish landrace from the south-east Anatolia, characterized by late heading and cold resistance, 7- Dorato: a late heading genotype, known by drought resistance. The Algerian genotypes Bousselam, Mohamed Ben Bachir (MBB) and Waha were used as check genotypes as they are widely cultivated in Algeria and represent three distinct heading stages. Waha is an early heading and a cold-tolerant genotype. Bousselam is recognized as a mid-early drought-tolerant genotype, while, MBB is a late heading landrace that is tolerant to both drought and cold and is characterized by high straw yield (Table 1).

Table 1. Names, origins, and genealogy of the studied 10 durum wheat genotypes.

GENOTYPE	ORIGINE /COUNTRY	HEADING CLASS	GENEALOGY
Icaverve	ICARDA	Early-heading	Azeghar1/4/IcamorTA0462/3/Maamouri 3// Vitron/Bidra1/5/Mgn13/Ainzen1
Margherita	ICARDA	Early-heading	Terbo1975/Geruftel12
Minosse	Italy	Early-heading	San CarloxDL
Om Rabia	Tunisia	Early-heading	JoriC69/Haurani
Saragolla	Italy	Early-heading	Iride/PSB0114
Waha	Algeria	Early-heading	Plc/Ruff//Gta/Rtte
Bousselam	Algeria	Mid-early heading	Heider/Martes//Huevos de Oro
Sorgul	Turkey	Mid-early heading	Landrace-South East Anatolia
Dorato	Italy	Late-heading	FZ512xIDSN-18 168
MBB	Algeria	Late-heading	Selection from local population

Field Experiment and Crop Management

Experimental trials were conducted across all the three seasons using a Randomized Complete Design (RCD) with three replicates as the standard protocol. Seeding was done in December by hand broadcasting, following conventional tillage using a disk plough and cover-crop. Each genotype was sown at 300 seeds m⁻² rate in an area of 1.2 m², comprising five rows with 0.20 m row-to-row distance. During all three seasons, field trials were setup on a fallow and conducted under rainfed conditions without any supplementary irrigation. In 2020-2021 season, NPK (15-15-15) fertilization was done on December 20th and Urea (46%) application was done on February 27th, followed by herbicide treatment, using Topik™ (080EC) (Active ingredient: Clodinafop-propargyl) on April 4th and Traxos™ (050EC) (Active ingredient: Pinoxaden+Clodinafop-propargyl) on April 18th. In 2021-2022 season we used NPK (4-20-25), applied on December 22nd while maintaining the same Urea application rate on April 6th, with chemical weeding using Topik™ on March 13th and Traxos™ on March 3rd. The 2022-2023 season maintained the same fertilizer combination as the previous year, with NPK (4-20-25) applied on December 12th and Urea on March 9th, but relied solely on Topik™ herbicide treatment on February 20th. Noting that the major provided element is N (77.6-88.6kg/ha) followed by P and K (Table 2). Local extension recommendation advises (60–100 kg) of N and (40–60kg) of P₂O₅, while K is generally not a primary concern for cereals.

Table 2. Seeding dates and fertilization during the three seasons.

SEASON	SEEDING DATES	FERTILIZATION (KG/HA)		
		N	P ₂ O ₅	K ₂ O
2020-2021	Dec 20th, 2020	88.6	15	15
2021-2022	Dec 22th, 2021	77.6	20	25
2022-2023	Dec 6th, 2022	77.6	20	25

According to Aycicek and Yildirim (2006), wheat field trials studies include, yield components such as plant density, plant height, grain number per spike, grain weight per spike, 1000 kernels weight and time to heading, indicating their importance in selection criteria.

In our study, period to heading (HEAD) consists of counting the number of days from January 1st to heading as the Julian date when the 50% of the spikes in a plot had fully emerged from the flag leaf sheath (Ma et al., 2024). Plant height (PH, in cm) was measured from the soil surface to the tip of the spike (excluding awns). At maturity, plants of the central row were manually harvested and the following traits were recorded: The total aboveground biomass weight (BIO, t ha⁻¹), including straw and spikes. The number of spikes by square meter (SPMNO) was estimated based on the number of fertile culms. Spikes were threshed manually, and yield components were then assessed including: the number of seeds per spike (fertility, FERT), grain yield per spike (GYS, g), total grain yield (GY, t ha⁻¹), thousand-kernel weight (TKW, g), the number of seeds per square meter was calculated using the formula $GY/TKW \times 1000$. Finally, the harvest index (HI, %) was calculated as: $(GY/BIO) \times 100$. Where BIO represents the total aboveground biomass (t.ha⁻¹).

Climate Data

Climatological data including decadal rainfall and mean temperature across three growing seasons (2020-2021, 2021-2022, and 2022-2023). This temporal scale was used to fine the analysis and emphasizes the impact of critical developmental on wheat productivity. Weather data were obtained from the Meteorological station located at the University Ferhat ABBAS campus. The weather station is equipped with a professional HOBO® data logger designed for multi-channel climate monitoring.

Data analysis

Data analysis was conducted using Analysis of Variance (ANOVA) using the General Linear Model (GLM) approach, where significant differences were considered at $p < 0.05$, $p < 0.01$ and $p < 0.001$. Post-hoc Least Significant Difference (LSD) tests were used after significant ANOVA at $p < 0.05$. This statistical approach was chosen to evaluate the effects of three factors: Genotype (G), season (S) and Heading Earliness class (HE) as well as mutual interactions. Heading date classification (HE) categorizes wheat genotypes into three temporal groups: early, mid-early, and late heading. This trait is important in semi-arid environments where genotypes face dual temperature stresses. In these regions, wheat genotypes must successfully develop within a narrow climatic window bounded by contrasting temperature extremes. Cold stress during early growth stages inhibits development and reduces spike fertility, while terminal heat stress poses an increasingly severe threat due to climate change. The reproductive phase is particularly vulnerable, with brief exposure to high temperatures (approximately 40°C for just two hours during anthesis) sufficient to compromise pollen viability and shorten grain filling periods.

Categorical Principal Component Analysis (CATPCA) was also performed, which is valuable for analyzing complex agricultural datasets as it handles mixed measurement levels and nonlinear relationships between variables (Linting et al., 2007), allowing visualization of interactions between factors that traditional methods might miss (Kaplan, 2004). This analytical approach is superior to standard PCA when dealing with categorical variables, making it more suitable for multi-seasonal agricultural trials (Blasius and Thiessen, 2012). Yield stability analysis is crucial for identifying genotypes that perform constantly across diverse seasons and ensuring reliable production. The following stability indices were used: Kang's rank-sum (combining yield performance and stability), Wricke's ecovalence (measuring a genotype's contribution to G x S interaction). These statistical tools enable breeders to select resilient, high-yielding genotypes and so reducing farmer risk. In this work, SPSS V.26 software was used to perform ANOVA and CATPCA, while the "metan" package was employed for computing yield stability parameters within the RStudio environment.

Results

Rainfall and temperature patterns

The rainfall regime during the study period confirms the erratic nature of rainfall in semi-arid environments. The 2020-2021 growing season recorded a total rainfall of 216.9mm, showing two moderate adjacent rainfall events (higher than 20 mm) in early season and a considerable precipitation event (80 mm) occurring in late season. The 2021-2022 season noted a total rainfall of 269.48mm, with a more even distributed rainfall pattern with multiple events of moderate intensity throughout the middle part of the

growing period, finishing by an intense rainfall event (exceeding 100 mm) near season's end. The 2022-2023 season with a total rainfall of 259.3mm, presented a concerning scenario with prolonged dry periods punctuated by isolated and small rainfall events, until two significant precipitation events in close succession at the season's end, representing 45% of the total rainfall (Figure 1).

Temperature fluctuations across the seasons revealed remarkable patterns with significant implications for wheat physiology and development. The 2020-2021 season maintained relatively stable temperatures, within the optimal range of wheat development (5-15°C). In contrast, 2021-2022 season showed greater variability, where decadal temperatures fall to approximately 0°C during the sixth decade (Figure 1), and daily minimum temperatures reaching -4.2°C on February 28th and March 5th during 2022-2023 season.

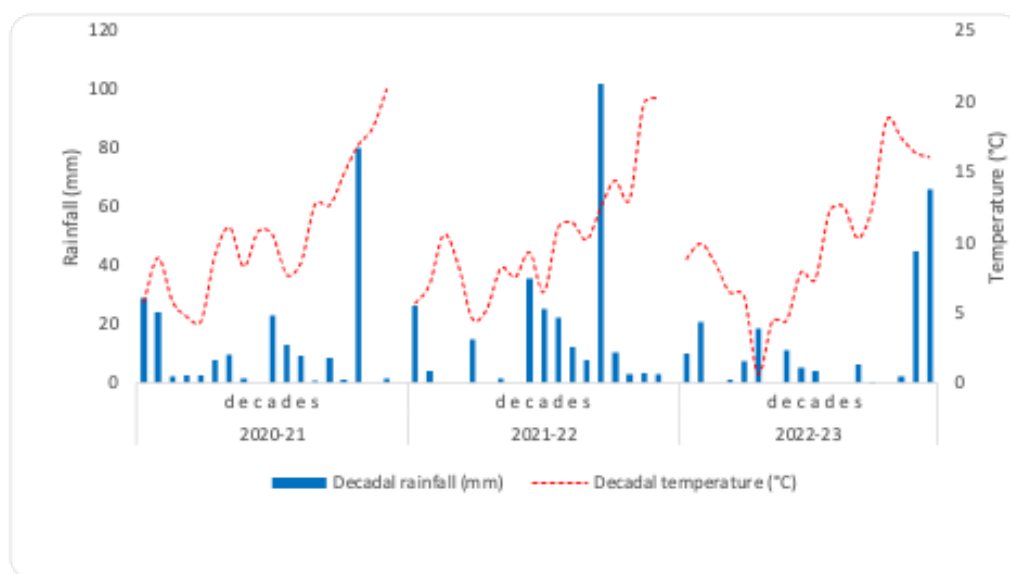


Figure 1. Decadal Temperature and rainfall during the growing seasons

Performance analysis of wheat yield components across heading periods

Analysis of wheat yield components across heading stages revealed significant patterns. HEAD was high in Late Heading Genotypes (LHG) (134 days) during 2021-2022 season, where the Algerian landrace MBB recorded the longest HEAD across all seasons (Table 3). Also, PH reached high mean in LHG (53.95cm), MBB recorded 89.3cm in 2021-2022, while Turkish genotype Sorgul had the highest PH (101.5cm). However, Early heading genotypes (EHG) showed lowest PH average for all seasons (44.05cm) (Table 3). FERT noted the highest average in (LHG) of 28.89, it was maximized during 2021-2022 season (35.63), where Saragolla achieved a maximum fertility of 54.50. However, the lowest FERT (22.91) was recorded with (EHG), meanwhile, 2022-2023 season had low FERT grand average (17.06). Om Rabia showed the lowest value of fertility (8.94) during 2020-2021 (Table 3). TKW reached analogous averages in all phenological stages for all seasons. While it was maximized during 2020-2021 with a grand average of 43.78g. The Algerian genotype Bousselam achieved a maximum TKW of 54.50g in 2020-2021. However, the lowest TKW grand average (29.22g) was recorded in 2022-2023. Saragolla had the lowest value of TKW (22.89g) during 2022-2023 (Table 3). SPMNO attained a high average in (EHG) of 354, followed by (LHG) and (MEHG) with 341 and 309 respectively. SPMNO

was maximized during 2021-2022 season (463), where the Algerian genotype Waha noted a maximum SPMNO of 601. However, 2022-2023 season recorded the lowest SPMNO grand average (248.92). Also, Waha recorded a minimum value of SPMNO (150) during 2022-2023 (Table 3). The averages of SMNO were higher in (LHG) with 9057 seed.m⁻² followed by (EHG) and (MEHG). During 2021-2022, SMNO grand average was extremely high (17779) compared to 4413 in 2020-2021 and 3148 in 2022-2023 season. In general, (EHG) performed best in 2020-2021 where Saragolla showed a high SMNO of 25114. The lowest SMNO grand average was noted in 2020-2021, and the extreme lowest value was recorded with Saragolla (2357) in 2022-2023 season (Table 3). BIO showed highest means in both (LHG) and (EHG) of 9.74t ha⁻¹, while BIO was maximized during 2021-2022 season (18.44 t ha⁻¹), where Om Rabia achieved a maximum biomass of 23.01 t ha⁻¹. However, the lowest BIO (9.22 t ha⁻¹) was recorded in (MEHG). 2022-2023 season had the lowest BIO grand average of 4.49 t ha⁻¹, where the Algerian genotype Waha showed the lowest value of BIO (3.70 t ha⁻¹) during 2022-2023 (Table 3). The average of GY was the high in (EHG) at 2.3 t ha⁻¹, followed by (LHG) and (MEHG). During 2021-2022, GY grand average was high (4.81 t ha⁻¹) compared to 1.37 t ha⁻¹ in 2020-2021 and 0.38 t ha⁻¹ in 2022-2023. In general, EHG performed best in 2020-2021 where Saragolla showed the highest recorded GY at 6.8 t ha⁻¹. The lowest GY grand average was noted in 2022-2023 when the lowest overall value was recorded for Saragolla at 0.22 t ha⁻¹ (Table 3). For the Harvest index, it attained 20% in (EHG) and (MEHG), HI was maximized during 2021-2022 season (26%), where Saragolla had a maximum HI of 32%. However, 2022-2023 season recorded the lowest HI grand average (8%). While Waha and Minosse recorded the minimum values of HI (5%) during 2022-23 (Table 3).

Analysis of wheat genotype and seasonal effects on yield components

Through ANOVA, exploring the effects of genotype (G), season (S), and Heading Earliness (HE) across the three seasons. Results showed that Season factor affected all parameters ($p < 0.01$), while genotype factor significantly impacted yield parameters namely HEAD, PH, FERT, TKW and SMNO. However, G x S interaction was not significant for TKW, HI and BIO. The GLM model explained high proportion of variance for most traits (R^2 : 0.60-0.96). Lower values of R^2 were noted for SPMNO and HI (0.6) (Table 4).

The LSD post-hoc analysis provides valuable insights into genotype performance variability across wheat development variables over three seasons. The results reveal interesting patterns of genotypic differentiation and seasonal stability (Table 5). HEAD is the most discriminating trait in all three seasons. Genotypes Icaverve, Margherita, Minosse, and Om Rabia tend to consistently have the earlier heading across seasons, while Dorato and MBB appear to have late heading date as it was hypothesized according to the heading factor. PH demonstrates seasonal variability in genotypic differentiation patterns. During 2020–2021 and 2021–2022, clear statistical groupings emerge, with most genotypes (Icaverve, Margherita, Minosse, Om Rabia, Saragolla, Waha, Bousselam) clustering in the "a" or "ab" groups, indicating similar and relatively tall plant stature. Sorgul and Dorato consistently occupy intermediate positions ("b" group), while MBB has the longest PH (group "c") across 2020-2021 season. In 2021-2022 FERT reveals significant genotypic differences. All genotypes share the "a" or "ab" grouping, indicating the lowest spike fertility. Saragolla with "b" grouping, indicating a high FERT, and statistically superior to the "a" group. TKW results reveal a moderate genetic hierarchy across 2020-2021 season, with three genotype clusters: one group (Om Rabia and Saragolla) producing lighter kernels in group "a", Intermediate group (Icaverve, Margherita, Minosse, Waha, Dorato, MBB, Sorgul), and finally, "b" group with only Bousselam; recording heavier seed weights.

SPMNO reveals Dorato as the top performer for spike density across 2022-2023 season, with most genotypes clustering in “a” and “ab” groups, indicating limited variation. In 2021-2022, SMNO was lowest for Margherita (group “a”), intermediate for the majority of genotype within “ab”, “abc”, and “bc” groups and highest for Saragolla in group “c”. In 2021-2022, results show genotypic effect on GY, with two distinct performance clusters. The consistently low-yielding group (a) including Bousselam, while the superior performer in group “b” (Saragolla). However, the remaining genotypes have intermediate GY performances “ab”.

Table 3. Averages for yield components according to Season, Heading Earliness stage and Genotypes: days to heading (HEAD), plant height (PH), number of seeds by spike (FERT), thousand kernel weight (TKW), number of spikes by square meter (SPMNO), number of seeds by square meter (SMNO), Total aboveground biomass (BIO), grain yield (GY), and harvest index (HI)

SEASON	EARLY HEADING GENOTYPES (EHG)							MID-EARLY HEADING GENOTYPES (MEHG)			LATE HEADING GENOTYPES (LHG)			GRAND AVG	
	ICAVERVE	MARGHERITA	MINOSSE	OM RABIA	SARAGOLLA	WAHA	AVG. EHG	BOUSSELAM	SORGUL	AVG. MEHG	DORATO	MBB	AVG. LHG		
HEAD	1	106	106	108	107	110	108	107.5	114	116	115.17	118	119	118.67	111.27
	2	128	125	126	126	127	126	126.33	128	128	128.17	133	135	134	128.23
	3	108	106	104	105	108	106	106.06	110	111	110.5	115	118	116.83	109.1
	Avg	114±5.7	112.33±5.1	112.66±5.5	5	112.66±5.4	115±4.9	113.33±5.2	113.29±5.33	117.33±4.4	118.33±4.1	117.94±4.31	122±4.54	124±4.49	123.16±4.44
PH	1	36.80	38.50	30.00	36.10	31.70	33.50	34.42	39.20	44.40	41.82	38.40	59.00	48.70	38.75
	2	71.30	74.60	64.70	78.70	66.70	71.50	71.24	70.30	101.50	85.90	77.40	89.30	83.37	76.60
	3	30.10	26.90	24.70	27.50	25.10	24.80	26.51	32.00	27.10	29.53	28.80	30.70	29.78	27.77
	Avg	46.06±10.4	46.66±11.7	39.8±10.2	47.43±12.9	41.16±10.5	43.26±11.7	44.05±11.25	47.16±9.5	57.66±18.3	52.41±13.97	48.2±12.13	59.66±13.81	53.95±12.81	47.7±12.07
FERT	1	11.94	16.56	15.06	8.94	15.11	17.67	14.21	19.94	22.67	21.31	22.22	25.72	23.97	17.58
	2	32.06	33.33	39.22	39.39	54.50	37.28	39.30	34.11	34.56	34.33	47.39	34.50	40.94	38.63
	3	19.22	12.56	12.33	16.11	15.44	15.78	15.24	20.17	15.44	17.81	21.56	22.00	21.78	17.06
	Avg	21.07±4.8	20.81±5.2	22.2±6.9	21.48±7.5	28.35±10.6	23.57±5.6	22.91±6.69	24.74±3.8	24.22±4.5	24.48±4.1	30.39±6.94	27.4±3.02	28.89±4.94	24.42±5.8
TKW	1	44.33	45.33	47.17	38.17	37.67	47.17	43.31	54.50	41.00	47.75	39.83	42.67	41.25	43.78
	2	32.03	33.37	36.38	36.28	30.59	30.36	33.17	29.17	28.42	28.80	34.79	29.84	32.32	32.12
	3	29.34	29.56	35.17	29.50	22.89	23.75	28.37	32.41	26.26	29.33	32.17	31.17	31.67	29.22
	Avg	35.23±3.7	36.08±3.8	39.57±3.1	34.65±2.1	30.38±3.4	33.76±5.6	34.95±3.59	38.69±6.5	31.89±3.7	35.29±5.08	35.59±1.83	34.56±3.32	35.08±2.52	35.04±3.63
SPMNO	1	430	373	316	371	291	300	347	223	243	233	311	320	315	318
	2	580	368	498	412	463	601	487	460	431	445	405	408	406	463
	3	306	255	240	276	153	150	230	232	268	250	373	233	303	248.92
	Avg	438±6	332±31	351±62	353±32	302±73	350±108	354±60	305±63	314±5	309±55	363±22	320±41	341±26	343±51
SMNO	1	3083	3624	2384	2481	3298	2473	2891	3003	3598	3301	3553	3981	3767	3148
	2	18524	12529	19429	16310	25114	22157	19010	14764	14970	14867	19179	14817	16998	17779
	3	6016	3510	3020	4449	2357	2596	3658	5330	4042	4686	7691	5125	6408	4413
	Avg	9207±386	6554±2439	8277±455	4	7746±3526	10256±6069	9075±5340	8519±4286	7699±2935	7536±3036	7618±2977	10141±3816	7974±2806	9057±3300
BIO	1	6.56	6.49	5.14	5.07	5.87	5.58	5.78	6.24	5.89	6.06	6.13	7.05	6.59	6.00
	2	21.13	13.62	17.86	23.01	21.92	18.22	19.29	13.53	20.46	16.99	17.32	17.29	17.31	18.44
	3	4.49	4.10	4.27	4.50	3.97	3.70	4.17	4.36	4.89	4.62	5.75	4.93	5.34	4.49
	Avg	10.72±4.2	8.07±2.3	9.09±3.5	10.86±4.9	10.58±4.6	9.16±3.7	9.74±3.91	8.04±2.3	10.41±4.1	9.22±3.18	9.73±3.09	9.75±3.11	9.74±3.1	9.64±3.6
GY	1	1.39	1.70	1.12	0.95	1.24	1.16	1.26	1.58	1.49	1.53	1.42	1.70	1.56	1.37
	2	5.46	3.96	5.44	5.04	6.80	5.23	5.32	3.14	4.67	3.90	4.86	3.50	4.18	4.81
	3	0.54	0.25	0.24	0.53	0.22	0.26	0.34	0.46	0.51	0.49	0.49	0.32	0.40	0.38
	Avg	2.46±1.2	1.97±0.8	2.26±1.3	2.17±1.1	2.75±1.6	2.21±1.2	2.3±1.24	1.72±0.6	2.22±1.02	1.97±0.82	2.25±1.08	1.84±0.75	2.04±0.91	2.18±1.09
HI	1	0.16	0.21	0.25	0.14	0.14	0.30	0.20	0.30	0.27	0.28	0.28	0.29	0.29	0.23
	2	0.27	0.29	0.30	0.23	0.32	0.29	0.28	0.23	0.23	0.23	0.28	0.20	0.24	0.26
	3	0.10	0.06	0.05	0.12	0.05	0.07	0.07	0.10	0.11	0.10	0.09	0.06	0.07	0.08

Avg	0.17±0.04	0.18±0.05	0.2±0.06	0.16±0.02	0.17±0.06	0.22±0.06	0.18±0.04	0.21±0.04	0.2±0.03	0.2±0.04	0.21±0.05	0.18±0.05	0.2±0.05	0.19±0.04
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Analysis of wheat genotype and seasonal effects on yield components

Through ANOVA, exploring the effects of genotype (G), season (S), and Heading Earliness (HE) across the three seasons. Results showed that Season factor affected all parameters ($p < 0.01$). while genotype factor significantly impacted yield parameters namely HEAD. PH. FERT. TKW and SMNO. However. G x S interaction was not significant for TKW. HI and BIO. The GLM model explained high proportion of variance for most traits (R^2 : 0.60-0.96). Lower values of R^2 were noted for SPMNO and HI (0.6) (Table 4).

Table 4. Effects of genotype (G). season (S). and their interactions (G x S) on yield components: days to heading (HEAD). plant height (PH). number of seeds by spike (FERT). thousand kernel weight (TKW). number of spikes by square meter (SPMNO). number of seeds by square meter (SMNO). Total aboveground biomass (BIO). grain yield (GY). and harvest index (HI)

	SOURCE OF VARIATION				R^2
	GENOTYPE (G)	SEASON (S)	G x S		
df ₁	9	2	18		
Mean square					
HEAD	152***	3147**	8**		0.96
PH	307***	18291***	112***		0.93
FERT	97***	4360***	81**		0.78
GYS	0.06ns	9***	0.1**		0.87
TKW	67***	1735***	39ns		0.68
SPMNO	13799ns	350124***	13705*		0.60
SMNO	12714192**	1897460300***	19936452***		0.91
BIO	10ns	1747***	11ns		0.82
GY	0.64ns	160***	1.23**		0.89
HI	0.003ns	0.28***	0.007ns		0.60

*1: degrees of freedom. *, **, ***. indicate significance levels: at $p < 0.05$. $p < 0.01$ and $p < 0.001$ respectively and (ns) no-significance.*

Table 5. LSD test evaluating genotypic differences across season

	SEASON	ICAVEERVE	MARGHERITA	MINOSSE	OM RABIA	SARAGOLLA	WAHA	BOUSSELAM	SORGUL	DORATO	MBB
		HEAD	2020-2021	a	a	a	a	ab	a	bc	bc
	2021-2022	a	a	a	a	a	a	a	a	b	b
	2022-2023	abc	a	a	a	abc	ab	bc	c	d	d
PH	2020-2021	ab	ab	a	ab	a	a	ab	b	ab	c
	2021-2022	a	a	a	a	a	a	a	b	a	a
FERT	2021-2022	a	a	a	a	b	a	a	a	ab	a
TKW	2020-2021	ab	ab	ab	a	a	ab	b	ab	ab	ab
SPMNO	2022-2023	ab	ab	ab	ab	a	a	ab	ab	b	ab
SMNO	2021-2022	abc	a	abc	ab	c	bc	ab	ab	abc	ab
GY	2021-2022	ab	ab	ab	ab	b	ab	a	ab	ab	ab

Genotypes sharing common letters belong to the same statistical group. indicating no significant difference between their means. while genotypes with completely different letters represent

significantly different performance levels ($p < 0.05$). Seasons with no significant ANOVA are not shown.

days to heading (HEAD), plant height (PH), number of seeds by spike (FERT), thousand kernel weight (TKW), number of spikes by square meter (SPMNO), number of seeds by square meter (SMNO), grain yield (GY).

HE significantly affected ($p < 0.01$) PH and FERT (Table 6) but not for the rest of components. HE x S interaction was significant for PH, GYS, SMNO, GY, and HI, showing that heading earliness effects vary by season. The coefficient of determination (R^2) ranges from moderate (0.51 for SPMNO) to high (0.88 for PH) (Table 6).

In this study, we take into account HE as factor; to reinforce this hypothesis, it was required to compare genotypes with the same heading class. Therefore, a series of ANOVA tests was conducted at ($p < 0.05$) for all variables across all seasons. Results showed no significant differences between genotypes within the same phenology, indicating a consistent similarity between genotypes in spite of the seasonal fluctuations.

Table 6. Effects of Heading Earliness (HE), season (S), and their interactions (HE x S) on yield components: plant height (PH), number of seeds by spike (FERT), thousand kernel weight (TKW), number of spikes by square meter (SPMNO), number of seeds by square meter (SMNO), Total aboveground biomass (BIO), grain yield (GY), and harvest index (HI)

SOURCE OF VARIATION					
	HEADING EARLINESS (HE)	SEASON (S)	HE x S		
	df ¹	2	2	4	R ²
Mean square	PH	718 ^{***}	14679 ^{***}	149 ^{**}	0.88
	FERT	264 ^{**}	2787 ^{***}	90ns	0.72
	GYS	0.06ns	6 ^{***}	0.21 ^{***}	0.84
	TKW	1.9ns	1372 ^{***}	70ns	0.58
	SPMNO	12408ns	211856 ^{***}	19467ns	0.51
	SMNO	11359552ns	1238189537 ^{***}	22397469 [*]	0.85
	BIO	3ns	1180 ^{***}	7ns	0.80
	GY	0.72ns	102 ^{***}	2 ^{**}	0.87
	HI	0.004ns	0.21 ^{***}	0.01 [*]	0.61

¹: degrees of freedom. *, **, *** indicate significance levels: at $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively and (ns) no-significance.

The Categorical Principal Component Analysis (CATPCA) biplot of wheat yield components revealed critical relationships across three growing seasons with two dimensions, explaining 88.58% of total variance (Dimension 1: 73.06%, Dimension 2: 15.52%). Strong positive correlations existed between GY, PH, FERT, SMNO, BIO, and HEAD, while HI showed moderate dependence to both dimensions. However, TKW loading was greater on Dimension 2 (Figure 2). The season 2020-2021 centroid aligned closely with TKW. However, 2021-2022 centroid was more associated with the majority of components.

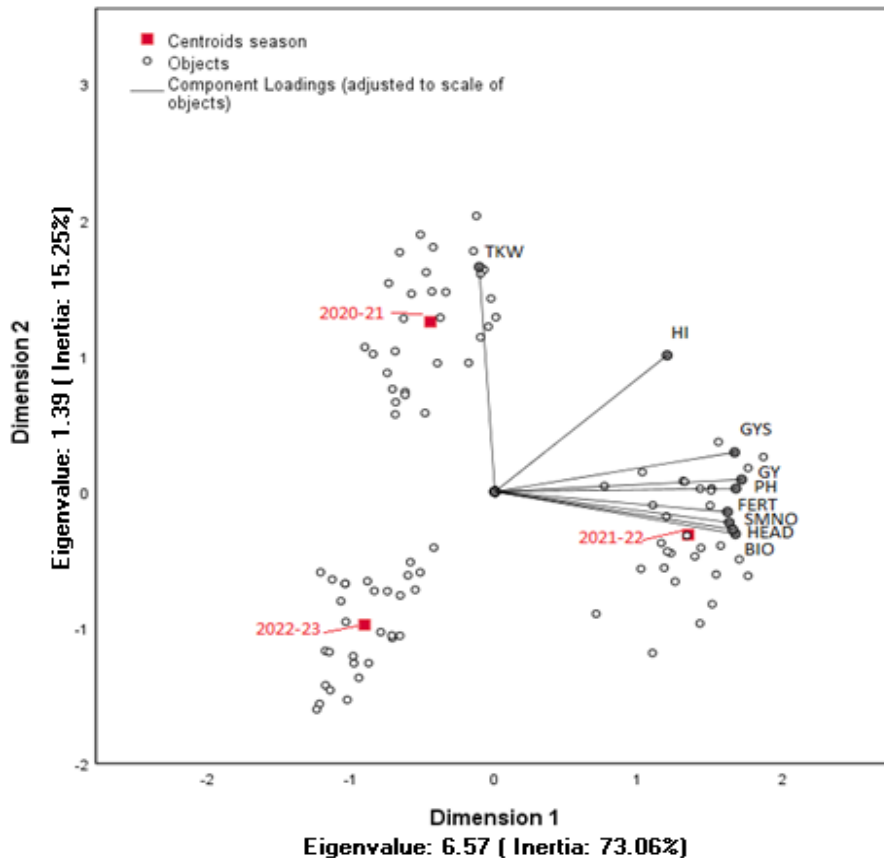


Figure 2. Biplot of wheat yield components over the three seasons

Integrated stability and yield performance

The analysis of wheat genotype performance revealed a complex interaction between yield potential and environmental stability, which is critical for developing resilient farming systems. Based on the stability analysis results presented in the table 7, several key insights emerge:

Icaverve presents an optimal combination of high yield (2.46 ± 0.8 t/ha) with excellent stability metrics (Rank-Sum: 5, Ecovalence: 0.222). Dorato demonstrates exceptional stability with the lowest Ecovalence (0.002) and excellent Kang's Rank-Sum (5), indicating minimal contribution to genotype \times environment interaction. Similarly, Sorgul exhibits outstanding stability (Ecovalence: 0.045, Rank-Sum: 7), making both genotypes ideal candidates for broad adaptation strategies.

The data reveals classic yield-stability relationships where Saragolla, despite achieving the highest grain yield (2.75 ± 1.02 t/ha), exhibits moderate stability, and maximal contribution to genotype \times environment interaction (Ecovalence: 3.052); a figure of yield-stability trade-offs.

The three Algerian genotypes show contrasting adaptation patterns: Bouselam demonstrates low stability (Rank-Sum: 19) and lower yield potential (1.72 ± 0.41 t/ha), while MBB exhibits intermediate performance across all metrics. However, Waha shows moderate stability (Ecovalence: 0.235 and Rank-Sum: 10) with reasonable yield, suggesting good adaptation to local conditions. Introduced genotypes demonstrate superior overall performance compared to local genotypes, with higher yield (2.3 ± 0.09 t/ha vs.

1.92±0.15 t/ha), better stability ranking (Kang's Rank-Sum: 9.14 vs. 15.33), and improved environmental consistency (Ecovalence: 0.68 vs. 1.19).

Table 7. Detailed metrics for grain yield potential and stability analysis

GENOTYPE	GY±SE	KANG'S RANK-SUM	WRICKE'S ECOVALENCE
Icaverve	2.46±0.8	5	0.222
Margherita	1.96±0.58	15	0.7
Minosse	2.27±0.85	9	0.465
Om Rabia	2.17±0.78	12	0.255
Saragolla	2.75±1.02	11	3.052
Sorgul	2.23±0.64	7	0.045
Dorato	2.25±0.69	5	0.002
Introduced genotypes	2.3±0.09	9.14	0.68
Bousselam	1.72±0.41	19	2.193
MBB	1.83±0.52	17	1.147
Waha	2.21±0.78	10	0.235
Local genotypes	1.92±0.15	15.33	1.19

Relationship between grain yield and stability in wheat genotypes

A clear correlation between grain yield and stability is shown, depicted by a negative slope regression (Figure 3). Grain yield is plotted against a combined stability index (Kang's Rank-Sum), where lower stability index values indicate higher yield stability. Genotypes such as Saragolla achieve higher grain yield but at the cost of lower stability. This trade-off is a crucial consideration for breeders aiming to optimize both productivity and resilience under varying environmental conditions. The consistent R^2 value (0.495) and p-value (0.02) support this significant inverse relationship, although with some variations explained by other factors. Indeed, the trend line is well fitted to genotypes (Bousselam, MBB, Margherita, Om Rabia and Waha) in the upper left quadrant, but this fitting becomes less consistent in the right lower quadrant with Minosse, Sorgul, Dorato, Icaverve and Saragolla.

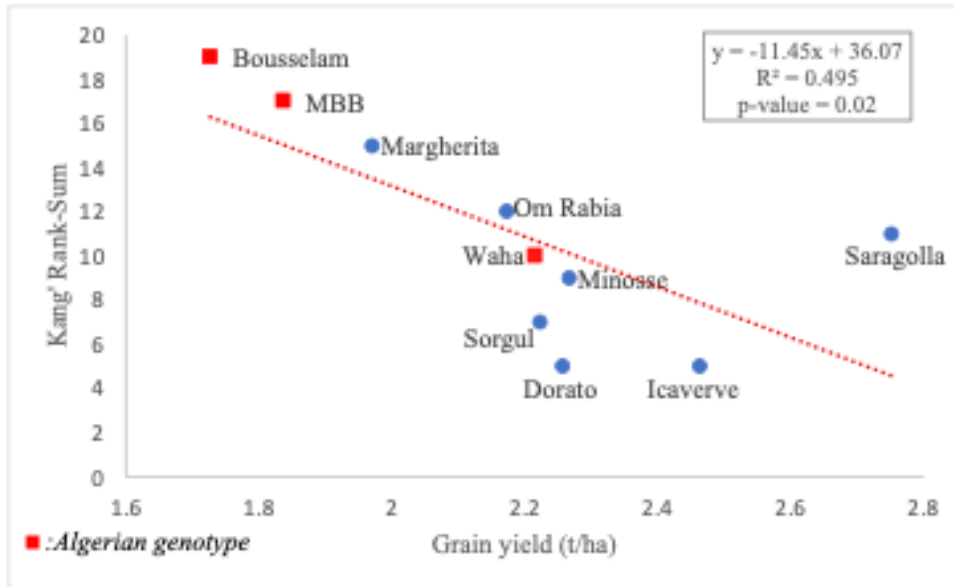


Figure 3. Relationship between grain yield and Kang's Rank-Sum stability indices.

Discussion

The climatological data analysis demonstrates a noticeable variability that characterizes semi-arid agricultural environments. The rainfall distribution impacts wheat production in semi-arid regions. Research indicates that both the quantity and timing of rainfall are crucial for optimizing wheat yield. Durum wheat is highly affected by unpredictable rainfall distribution, leading to significant variations in biochemical and physiological responses (Saghouri El Idrissi et al. 2023).

The erratic rainfall distribution across the three growing seasons aligns with Rockström et al. (2010) observations regarding temporal variability in such agro-ecosystems. The 2020-2021 season showed multiple moderate rainfall events in early season followed by a long drought period. This pattern creates a significant soil moisture discontinuity that could impact root development and nutrient uptake efficiency (Asseng et al. 2011). The 2021-2022 season showed the most favorable rainfall pattern with relatively uniform distribution (269.48mm) namely during the mid-season, while 2022-2023 presented a concerning situation with prolonged drought followed by concentrated terminal rainfall events (259.3mm total) that arrived too late to benefit grain filling but probably disrupted harvest operations. This pattern closely matches what Semenov and Porter (1995) identified as problematic "terminal rainfall" that fails to translate into yield benefits. It should be noted that 2022-2023 was weather-stricken harvest season for wheat cropping in north Algeria, where the total cereal production in 2022-2023 was estimated to be 20% below the previous five-year average (FAO, 2024).

Temperature fluctuations provided additional stress factors, particularly the concerning cold snap in the 2022-2023 season, where temperatures approached critical thresholds for wheat development. With temperatures falling to approximately 0°C during tillering stage and daily minimums reaching -4.2°C, these conditions likely reduced developmental processes. While, Shang et al (2021) confirm that wheat tillering is influenced by genetic, hormonal and environmental factors. According to Porter and Gawith (1999) the cardinal temperatures for wheat development are approximately 0°C as a baseline, 20-25°C as an optimal temperature, and 35°C as a critical heat threshold. Such cold periods can

significantly delay growth and damage developing tissues. These observations highlight the importance of temperature resilience in breeding programs targeting semi-arid environments, where both drought and temperature extremes may occur simultaneously. The climate pattern observed in Algeria can also be imputed to similar regions of North Africa. In Tunisia, wheat productivity is severely affected by rainfall distribution and climate projections indicate that these challenges will intensify, with rising temperatures expected to further reduce wheat yields (Khila et al. 2015). Similarly, Morocco faces dramatic reductions in rainfed wheat productivity, with modelling studies predicting potential yield decreases of up to 55%, mainly attributed to substantial declines in rainfall availability that may reach 40% in some regions (Brouziyne et al. 2022).

The performance analysis of wheat yield components across heading earliness stages reveals important adaptive strategies in response to the challenging climatic conditions. The significant variations observed in days to heading (HEAD) demonstrate the critical importance of phenological adaptation as emphasized by Semenov et al. (2014). (LHG) with extended vegetative phases could potentially exploit favourable moisture conditions when available, but this strategy did not consistently translate to yield advantages. Rebetzke et al. (2013) noted that excessive vegetative growth can compromise water-use efficiency, particularly in water-limited environments.

The superior performance of (EHG) in fertility, and grain yield (GY) during the favourable 2021-2022 season provided strong evidence for the effectiveness of the phenological escape strategy as marked by Reynolds and Langridge (2016a). However, in 2022-2023 season, where climatic conditions were unfavourable, (EHG) genotypes performances decreased drastically. This finding does not align with Flohr et al. (2017) research demonstrating early heading as a superior adaptation mechanism for variable climate patterns. The good performances of Saragolla across multiple yield components (FERT, SMNO, GY and HI) in 2021-2022 suggested an optimized balance of vegetative development, confirming so the early phenology's adaptation value (Shavrukov et al. 2017). HI varies due to genetic and environmental factors; modern breeding practices have significantly increased HI over time (Camargo-Alvarez et al. 2022). Genetic improvements have historically increased HI in wheat, primarily through breeding programs that focus on fertility and yield. HI averages were almost similar in all phenology classes spanning from 18% to 20%. However, during the favourable season (2021-22) HI grand average was higher. Porker et al. (2020) noted that HI is significantly impacted by environmental conditions, such as water supply and temperature during reproductive development.

The ANOVA results clarify the complex relationship between genetic factors and seasonal conditions. The significant genotype (G) effect on key developmental traits (HEAD, PH, FERT, TKW, SMNO) highlights the important role of genetic selection in determining yield potential. However, the stronger season (S) effect across all parameters confirms the substantial impact of environmental effect, as documented by Asseng et al. (2015). The significant GxS interaction for most traits except TKW, HI and BIO, supports observations made by Tsenov et al. (2023) about differential genotype responses to seasonal conditions and underscores the importance of breeding stable genotypes as noted by Martínez-Peña et al. (2023). Most traits have high R^2 (0.80-0.96), at contrast, low values were noted for SPMNO and HI (0.6), suggesting other factors influence these components (Lobell et al. 2007). Significant interaction G x S for HEAD is a key for seasonal response and adaptation (Mondal et al. 2013) (Table 4).

The significance of (HE) effect on PH and FERT, coupled with the significant HE x S interaction for several yield components, demonstrates that optimal phenological adaptation is contingent on specific seasonal conditions. This supports the conclusions drawn by Reynolds and Trethowan (2007) regarding the context-dependent characteristics of phenotypic adaptive traits. The moderate to high R^2 across various traits (0.51 for

SPMNO) to high (0.88 for PH) validates the substantial influence of phenological adaptation on wheat productivity. This outcome corroborates research showing the importance of phenological adaptation in wheat productivity (Slafer et al. 2005; Sadras and Slafer. 2012). However, the lower R^2 values for some traits suggest that other factors beyond HE stages, and season contribute significantly to their variation.

The CATPCA biplot provides valuable insights into the relationships between yield components across growing seasons. The strong positive correlations between GY, PH, FERT, SMNO, BIO, and HEAD indicate the coordinated nature of these physiological traits. However, the remarkable independence of TKW, loading solely on Dimension 2, supports the findings of Slafer (2003) on the relative independence of kernel weight regulation. This suggests a yield component compensation mechanism that could be targeted in breeding programs, to break the typical negative correlation between seed number and kernel weight through targeted selection approaches, as proposed by Fischer (2011). The distinctive position of seasonal centroids in the CATPCA biplot highlights the substantial influence of year-to-year climate variation on wheat performance, which is consistent with Reynolds et al. (2016b) statement saying that environmental fluctuations represent a major source of yield instability.

Stability indices represent sophisticated statistical approaches for evaluating genotype performance across diverse environmental conditions, providing major insights for genetic adaptability and phenotypic plasticity. Kang's rank-sum method introduces a non-parametric approach by ranking genotypes across different environments, allowing large assessment of consistent performance by a simultaneous integration of yield potential and stability (Kiliç et al. 2010; Sabaghnia et al. 2006). While, Wricke's ecovalence, alternatively, measures the contribution of individual genotype-environment interaction.

The stability analysis shows an important trade-off between yield potential and stability. Breeders often face this paradox where maximizing yield can reduce stability, reinforcing the need for breeding programs to balance both to enhance food security, especially in marginal environments (Yan & Hunt, 2001).

Yield stability is increasingly recognized as vital, several studies showed that many farmers prioritize it over sheer yield outcome (Macholdt & Honermeier, 2017). Icaerve and Dorato present an optimal combination of high yield with excellent stability metrics, representing what Kang (1988) described as the most desirable genotype profile - combining both high performance and environmental buffering capacity. Lowest Wricke's Ecovalence and excellent Kang's Rank-Sum, indicating minimal contribution to genotype \times environment interaction. This aligns with Wricke's (1962) original concept where lower ecovalence values represent greater phenotypic stability across environments. However, Saragolla, despite achieving the highest mean grain yield, exhibits the highest instability. This pattern supports Lin et al. (1986) observations that high-yielding genotypes often show greater sensitivity to environmental variations, reflecting their responsiveness to favorable conditions but vulnerability in marginal environments. This statement aligns with traditional perspectives on the yield-stability trade-off in plant breeding, where high-performing cultivars in optimal conditions may underperform in suboptimal environments (Pennacchi et al. 2019). The high instability observed in Margharita, Saragolla and Om Rabia, underlined the importance of comprehensive genotype screening that incorporates both yield potential and stability metrics. Performances of Saragolla, leading in FERT, GYS, GY, and HI, suggested an optimized phenotype that well-adjusted plant development with stresses management. This genotype warrants particular attention for breeding programs targeting productivity enhancement in semi-arid environments. Meanwhile, genotypes Icaerve, Dorato and Sorgul represented valuable genetic resources for stability criterion.

The severe yield reduction observed across all genotypes in stricken 2022-2023 season confirmed the devastating impact of drought combined with temperature stress. However, the relative advantage maintained by EHG even under these extreme conditions supports findings of Pourtabrizi et al. (2022) regarding the importance of early phenology as an adaptation mechanism in drought-prone conditions. However, (Kim and Kwon, 1985) reported that early heading significantly reduced grain yield per plant, primarily due to decreased spike number and fertility, highlighting the need for careful breeding strategies. The recommendation is particularly relevant in the context of climate change, where increased variability in precipitation patterns and temperature regimes is expected to amplify the threats faced by farmers in semi-arid climate. Table 8 provides an overview of the genotype's evaluations organized by performance potential, classifying introduced genotypes into three yield-stability performance levels: highest potential (Saragolla, Icaverve, Dorato), moderate performers (Minosse, Sorgul), and low-priority options (Om Rabia, Margherita), detailing their specific characteristics regarding yield and stability. The practical guidance for breeding programs, highlighting Icaverve, Dorato and Sorgul for stable germplasm development, Saragolla for yield enhancement initiatives, and cautioning against Margherita and Om Rabia due to their extreme environmental sensitivity.

The introduced materials have 19.8% yield advantage aligns with Ceccarelli and Grando (1996) observations that modern breeding programs often produce genotypes with enhanced yield potential. This pattern contradicts the common assumption that local varieties possess inherently superior adaptation to regional conditions, suggesting that modern breeding has successfully combined yield advancement with stability improvement, as documented by Trethowan and Crossa (2007). Waha approaches introduced genotype stability levels (Ecovalence: 0.235), suggesting potential for local germplasm improvement through targeted selection. However, the overall performance gap demonstrates what Braun et al. (2010) termed the "genetic gain differential" between systematic breeding programs and traditional varieties, where continuous selection pressure and genetic enhancement in introduced materials results in measurable improvements in both productivity and stability parameters.

Table 8. Performance Analysis for the introduced material and Breeding Recommendations

RANKING CATEGORY	GENOTYPES	CHARACTERISTICS	RECOMMENDATIONS
Highest Potential	Icaverve	Excellent stability, moderate yield	Prioritize for stable germplasm development; use as a stable baseline for breeding programs
	Dorato	Outstanding stability, competitive yield	Prioritize for stable germplasm development
	Saragolla	Highest yield, low stability	Use for yield enhancement programs in favorable environments Consider for intermediate breeding strategies; recommended for diverse agricultural environments
Moderate Performers	Minosse, Sorgul	Balanced yield and stability	Consider for intermediate breeding strategies; recommended for diverse agricultural environments

RANKING CATEGORY	GENOTYPES	CHARACTERISTICS	RECOMMENDATIONS
Low-Priority	Om Rabia	Highest environmental sensitivity	Avoid due to extreme variability; consider for further investigation to understand high variability
	Margherita.	Relative limited yield and stability	Not recommended
Contextual Recommendations	Icaverve. Dorato. Sorgul		Preferred for semi-arid environments

Conclusions

This article aimed to identify high-performing wheat genotypes with strong adaptability to semi-arid environments. The analysis highlights the significant influence of climatic variability wheat yield components, particularly across different classes of heading earliness. Favourable climatic conditions, such as well-distributed rainfall and moderate temperatures can significantly improve growth and productivity. In contrast, adverse conditions, such as drought, heat stress, or erratic rainfall, can severely hinder crop performance.

The successful application of these findings requires a collaborative effort involving policymakers, researchers, and local farmers. Such collaboration should prioritize targeted funding mechanisms, the development of innovative and climate-resilient breeding programs, and comprehensive farmer training initiatives to support the adoption of improved practices.

Future research directions should include:

To build on the insights of this study, future research should aim to:

- Conduct in depth exploration into genetic variability and genotype-environment interactions.
- Evaluate long-term genotype performance across multiple seasons and divers agroecological zones. And
- Adopt a multidisciplinary approach that integrates ecological, agronomic, and socio-economic dimensions of crop production.

This study underlines the dual influence of annual climatic variability and genetic potential in shaping wheat performance. Both local and newly introduced genotypes showed promise as potential catalyst for sustainable agricultural transformation in Algeria. However, the study also highlights key limitations. Yield potential, while important, is insufficient as a sole criterion for varietal selection; multi-seasonal and multi-locational trials are essential to validate stability and adaptability. Additionally, the lack of detailed climatic records (e.g., Evapotranspiration, radiation, CO₂, air humidity...) limits the ability to accurately attribute yield responses to specific climatic drivers.

Furthermore, the limited number of genotypes (n=10) restricts scope of genetic diversity explored. To address this, future studies should employ broader and more holistic screening strategies that balance genetic potential with sustainable crop management practices. Techniques such as conservation agriculture, supplementary irrigation and integrated soil-

water management must be considered to ensure crop resilience under increasingly unpredictable climatic conditions.

To conclude, this work contributes valuable insights into wheat genotype evaluation under semi-arid conditions, offering a foundation for future research and practical innovation aimed at enhancing food security and climate resilience in vulnerable regions.

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