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RESEARCH ARTICLE

Identifying high-yielding and stable durum wheat genotypes using G × E analysis in climate change context

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Abstract

Assessing durum wheat genotypes in varied environments is essential for evaluating yield stability and adaptability. This research evaluated the performance of 25 different durum wheat genotypes over three years (2020–2023) across 16 environments in Morocco. One objective was to evaluate how genotypes interact with varying environmental conditions (GEI) and to identify genotypes that combine high yield with stability across specific mega-environments. This analysis was conducted using a randomized complete block design with three replicates. The primary criteria for selection included grain yield, the AMMI Stability Value (ASV) and the Genotype Selection Index (GSI). Analysis revealed highly significant differences ($P<0.0001$) among genotypes, environments and their interactions (GEI). According to the AMMI analysis of variance, the total variation in yield was attributed to the environment (77.91 %), genotype (0.80 %) and GEI (5.93 %). Principal components (PC) 1 and 2 accounted for 51.9 % of the observed variation. Similarly, the GGE biplot demonstrated that PC1 and PC2 contributed 31.51 % and 18.67 % of the yield variation, respectively. Based on yield and ASV, G4, G16, G10, G23 and G5 demonstrated high performance, while G4, G9, G11 and G14 exhibited stability. According to the GSI, genotypes G4, G5, G23, G14 and G17 were most desirable. The findings highlight the substantial impact of GEI on yield variability, with genotype G16 emerging as optimal and G4, G5 and G17 being identified as favourable candidates for cultivation across five identified mega-environments, each suited to specific genotype adaptation. The identified high-performing genotypes can be integrated into Moroccan breeding programs to enhance durum wheat productivity and resilience to climate variability.

Keywords: climatic resilience; genotype selection index; Morocco; multi-environmental trials; *Triticum durum*; yield stability

Introduction

Wheat (*Triticum spp.*) is among the most significant and widely consumed cereal crops worldwide, producing an average of 740 million tons annually over the past decade. Wheat is the most commonly grown cereal crop worldwide, covering approximately 220 million hectares annually across diverse climates and geographical regions. Even if bread wheat represents more than 90 % of cultivated wheat, durum wheat (*Triticum turgidum, subsp durum Desf*, 2n = 4x = 28, AABB) spanning over 13.5 million hectares and contributing to a global yield of 33.8 million tons during the 2021 season (1, 2, 3). Durum wheat belongs to the Poaceae family, which includes other essential cereals such as rice, maize and barley. It is a tetraploid species (2n = 4x= 28) derived from two significant domestication events in the fertile Crescent around 10.000 years ago. The first event involved the transition from wild emmer (*T. turgidum ssp. dicoccoides)* to domesticated emmer (*T. turgidum spp. Dicoccum)*, marked by the loss of spike fragility, which facilitated harvesting. The second event involved transitioning from cultivated emmer to durum with the appearance of naked kernels or free-threshing kernels (4, 5).

Durum wheat faces significant productivity challenges in arid regions, with climate change expected to exacerbate these issues. The combined pressures of climate change and increasing food demand from population growth highlight the need to boost durum wheat production (6, 7). In Morocco, Durum wheat is a key cereal crop with a long history of cultivation, occupying over one million hectares each year. It is grown mainly across rainfed areas experiencing both rainy and dry seasons associated with erratic rainfall distribution within seasons (8).

Abiotic stress, particularly high temperatures and drought, significantly constrain global crop production (9). In its fifth report, the Intergovernmental Panel on Climate Change projected a rise in the global average temperature of 3.7°C by the century's end, which would significantly affect global agricultural production. The threat of climate change continues to have a detrimental effect on durum wheat yield and forecasts predict a decrease of up to 27 %

by 2050 (10, 11, 12). Under Mediterranean and semi-arid climates, selecting wheat genotypes with high WUE has proven effective for sustaining productivity under erratic rainfall patterns (13). Moreover, agronomic practices such as conservation tillage, deficit irrigation and precision agriculture enhance WUE by reducing soil evaporation and optimizing crop water availability (14).

Breeding is one of the most effective solutions for overcoming environmental stresses and reducing the adverse effects of climate change on agricultural production by developing new high-performing varieties that are resilient to a wide range of environmental conditions (15, 16). Improving the yield of durum wheat is a significant challenge for any breeding program in each country because current geopolitics means that each country must be self-sufficient by ensuring production that covers the needs of the local population. The long, laborious and expensive process of developing new varieties and evaluating existing varieties in more environments to identify a stable and high yield is a near-term solution to improve durum wheat production.

Genotype-by-environment interaction (GEI) describes the variability in genotype performance under various environmental conditions, often leading to reduced yield (17). Under prevailing climate change conditions, the GEI has become a great challenge for breeders, as it reduces selection efficiency and varietal recommendation accuracy. Therefore, it is necessary to properly assess the extent of the GEI on the trait of interest and address its drawbacks to select the best performance most effectively (1, 18). Multi-environment trials (METs) are essential for assessing genotypic stability, as the extent of GEI affects the mean performance of genotypes across environments (19).

Understanding GEI and crop stability is vital for decision-making, particularly in the final stages of variety introduction. It offers critical insights into breeding line adaptation, aids in screening new varieties for release and identifies optimal recommendation zones (20). Focusing on environments with significant variance in breeding programs is more efficient than expanding the number of test sites (21). Several statistical methods have been proposed for this purpose, with the Genotype × Environment Interaction (GGE) model, the Additive Main Effect and Multiplicative Interaction (AMMI) model and the Genotype Main Effect being the most widely used. The AMMI model integrates variance and principal component analysis, focusing on fixed effects without requiring external data or additional environmental or genotypic structures. It serves three key functions: model diagnostics, clarifying GEI and improving the accuracy of yield predictions (22).

The Genotype main effect and Genotype × Environment interaction biplot is an effective tool for visualizing relationships between genotypes and environments, aiding in identifying genotypes with consistent performance across diverse conditions (18, 23, 24). It helps pinpoint mega-environments with specifically adapted genotypes, assess yield and stability through the average environment coordinate approach and evaluate test environments (25). Various statistical methods are applied to interpret GEI, aiding in informed decisions for various recommendations (26).

In this context, the study aimed to (i) evaluate the performance of 25 durum wheat genotypes across diverse Moroccan environments, (ii) assess the impact of GEI on grain yield and (iii) identify the most productive and stable genotypes to recommend suitable varieties for specific mega-environments.

Materials and methods

Field experiments and plant material

The trials were conducted at seven experimental stations in Morocco: Sidi El Aydi (SEA), Marchouch (MCH), Annoceur (AN), Tassaout (TST), Jemaa Shaim (JSH), Sidi Allal Tazi (AT) and Douyet (DYT). These locations, managed by the National Institute of Agronomic Research (INRA), represent key durum wheat-growing areas. The study aimed to evaluate genotype performance and identify the top-performing varieties under varied environmental conditions over three consecutive crop seasons: 2020-21, 2021-22 and 2022-23.

The experimental material included 25 durum wheat genotypes comprising 23 Moroccan varieties and two elite lines from INRA Morocco (Table 1). The elite lines were chosen from advanced yield trials for their high yield potential and favourable agronomic and quality traits.

Experimental design and data collection

The investigation was undertaken using a randomized complete block design (RCBD) with three replicates. Every plot comprised six rows, each 5 meters long and spaced 0.2 meters apart, resulting in a total planted area of 6 m^2. The seeding rate was set at 300 seeds per m^2. Agronomic practices were aligned with local recommendations specific to each environment, with weed control implemented manually and chemically. Grain yield (GY) data were collected at maturity across all environments and seasons, measured over 6 m^2 and standardized to metric tons per hectare ($t.ha^{-1}$).

Statistical Analysis

Analysis of Variance

A two-way analysis of variance (ANOVA) was performed to evaluate the effects of genotype, environment and their interaction on yield across all environments studied.

Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype Main Effect and Genotype-by-Environment Interaction (GGE)

The "metan" package (27) was utilized for AMMI analysis as per standard procedure (28, 29). AMMI biplot analysis evaluated the adaptability and variation in durum wheat genotypes due to genotypic and environmental factors. Additionally, the AMMI Stability Value (ASV) (30) and Genotype Selection Index (GSI) (31) were calculated to identify the most stable genotypes, complementing the AMMI analysis.

Table 1. Name, origin and mean yield of the 25 durum wheat genotypes used in this study

No	Code	Genotype	Origin/ year of release	Mean yield (t ha^{-1})
1	G1	Amjad	INRA-Morocco /1995	2.16
2	G2	Amria	INRA-Morocco /2003	1.88
3	G3	Annoaur	INRA-Morocco /1993	1.96
4	G4	Boniduro	SEMILLAS BATTLE-Spain/2012	2.45
5	G5	Carioca	SERASEM-France/2005	2.33
6	G6	Chaoui	INRA-Morocco /2003	2.07
7	G8	Faraj	INRA-Morocco /2007	2.19
8	G9	Ginseng	FLORIMOND DESPEREZ-France/2009	2.25
9	G10	Irden	INRA-Morocco /2003	1.99
10	G10	Itri	INRA-Morocco /2016	2.35
11	G11	Hamadi	INRA-Maroc/2017	2.03
12	G12	Jabal	BENCHAIB-Morocco /2021	2.28
13	G13	Karim	INRA-Morocco /1985	2.15
14	G14	Kanakis	FLORIMOND DESPEREZ-France/2009	2.11
15	G15	Louisa	INRA-Morocco /2011	2.03
16	G16	LP4	INRA-Morocco /	2.42
17	G17	LP5	INRA-Morocco /	2.19
18	G18	Marouan	INRA-Morocco /2003	1.92
19	G19	Marzak	INRA-Morocco /1984	2.12
20	G20	Nachit	INRA-Morocco /2018	2.23
21	G21	Nassira	INRA-Morocco /2003	2.09
22	G22	Ourgh	INRA-Morocco /1995	2.03
23	G23	Prospero	FLORIMOND DESPEREZ-France/2007	2.34
24	G24	Tarek	INRA-Morocco /1995	1.91
25	G25	Tomouh	INRA-Morocco /1997	2.05

The GGE biplot was introduced to identify stable, high-yield genotypes capable of adapting to diverse environments (32). The GGE biplot model formulated was used in this study and the biplot analysis, including the basic biplot, the which-won-were, the mean vs. stability, the ranking genotypes and the ranking environments, were performed to assess the grain yield of twenty-five durum wheat genotypes (33). The R software and ggeplot2 package were used to create All of the AMMI and GGE biplots.

Results

Analyze variance, location description and characterization of grain yield

A high level of variability was observed across the 16 environments (Table 2), with the combined analysis of variance (ANOVA) revealing highly significant differences among genotypes, environments and GEI effects ($P < 0.0001$). The environments JSH (E3) and TST (E5) represent arid zones with and without irrigation input, respectively. SEA (E7, E12 and E16) represents a semi-arid zone. Allal Tazi (E1, E11 and E14) belong to the humid agroecological zone. The favourable zone was represented by two locations: Marchouch (E4, E10 and E13) and Douyet (E2, E8 and E15). The mountain zone is defined by Annoceur (E6 and E9).

The mean grain yield was 2.14 t.ha^{-1}, ranging from 0.31 t.ha^{-1} in E16 (SEA23) to 5.78 t.ha^{-1} in E2 (DYT20). Soil textures varied by location, with limestone clay in DYT and AT, vertisol in MCH, vertisol and limestone in JSH, clay loam in SEA, a combination of clay loam and limestone in AN and stony soil in TST. Based on mean yield, environments can be divided into three groups: environments with high yields (>4 t.ha^{-1}) are represented by E2 and E4, whereas those with low yields (< 2 t.ha^{-1}) are represented by E1, E3, E8, E10, E11, E13, E15 and E16. Environments E5, E6, E7, E9, E12 and E14 represented moderate-yielding environments (2 < t.ha^{-1} < 4).

Rainfall data for each environment are presented in Table 2. Rainfall across the 16 environments varied significantly, from a low of 78 mm in AN22 during the 2021-22 season to a high of 457.7 mm in AT21 during the 2020-21 season, with an average of 206.9 mm. Nine of the environments received below-average rainfall, while six received above-average rainfall. During the 2020-21 season, all locations except JSH21 and SEA21, in arid and semi-arid regions, received precipitation above the average. In contrast, all locations experienced below-average rainfall in the 2021-22 season. The 2022-23 season followed a similar trend, except for MCH23 and AT23, in favourable, humid areas. These findings classify the 2020-21 season as wet and 2021-22 and 2022-23 seasons as dry.

AMMI analysis

AMMI analysis of variance for grain yield

As shown in the AMMI ANOVA results (Table 3), grain yield among the 25 durum wheat genotypes was significantly affected by genotype (G), environment (E) and their interaction (GEI), with all effects being highly significant at $p < 0.001$. The environmental effects accounted for 77.91 % of the total mean square, followed by GEI effects (5.93 %) and genotypic effects (0.80 %). Additionally, AMMI analysis revealed that GEI can be divided into three main multiplicative terms, namely PC1, PC2 and PC3, which account for 63.5 % of the variation. This indicates that these three principal components significantly impacted the grain yield (Table 3). The high percentage of environmental effects was confirmed by the variation in the yield of the tested genotypes among the changing environments (Fig. 1). The yield varied from 0.11 t.ha^{-1} in E16 to 7.09 t.ha^{-1} in E2.

Table 2. Mean environment yield, location description and soil traits of the experimental sites

Environment (code)	Location	Cropping season	Longitude (E)	Latitude (N)	Altitude (m)	Soil type	Agroecological zone	Annual rainfall (mm)	Mean yield (t ha^{-1})
E1 (AT21)	Sidi Allal Tazi	2020-21	34° 31′	6° 19′	10,5	limestone clay	Humid irrigated areas	457,7	1.36
E2 (DYT21)	Douyet	2020-21	5°07	34°02	416	Clay limestone	Favorable rainfed areas	381.5	5.77
E3 (JSH21)	Jemaa Shaim	2020-21	10° 0′	32° 40′	170	limestone, vertisol	Arid Areas	196	0.83
E4 (MCH21)	Marchouch	2020-21	6°71	33°60'	410	vertisol	Favorable rainfed areas	367.30	4.75
E5 (TST21)	Tassaout	2020-21	7°24'	32°03'	465	stony	Arid irrigated areas	**	2.88
E6 (AN21)	Annoceur	2020-21	4°51	33°41'	1350	clay loamy, limestone	Mountain area	213*	2.84
E7(SEA21)	Sidi el Aidi	2020-21	7°37'	33°07'	240	Clay loam	Semi-Arid Areas	101.2	2.36
E8 (DYT22)	Douyet	2021-22	5°07	34°02	416	Clay limestone	Favorable rainfed areas	197.2	0.76
E9(AN22)	Annoceur	2021-22	4°51	33°41'	1350	clay loamy, limestone	Mountain area	78*	3.67
E10 (MCH22)	Marchouch	2021-22	6°71	33°60’	410	Vertisol	Favorable rainfed areas	107,90	0.42
E11 (AT22)	Sidi Allal Tazi	2021-22	34° 31′	6° 19′	10,5	limestone clay	Humid irrigated areas	144.6	0.74
E12 (SEA22)	Sidi el Aidi	2021-22	7°37'	33°07'	240	Clay loam	Semi-Arid Areas	112.4*	2.59
E13 (MCH23)	Marchouch	2022-23	6°71	33°60’	410	vertisol	Favorable rainfed areas	213,3	1.74
E14 (AT23)	Sidi Allal Tazi	2022-23	34° 31′	6° 19′	10,5	limestone clay	Humid irrigated areas	304,5	2.45
E15 (DYT23)	Douyet	2022-23	5°07	34°02	416	Clay limestone	Favorable rainfed areas	112,7	0.79
E16 (SEA23)	Sidi el Aidi	2022-23	7°37'	33°07'	240	Clay loam	Semi-Arid Areas	117*	0.31

**** fully irrigated; *** partially irrigated.

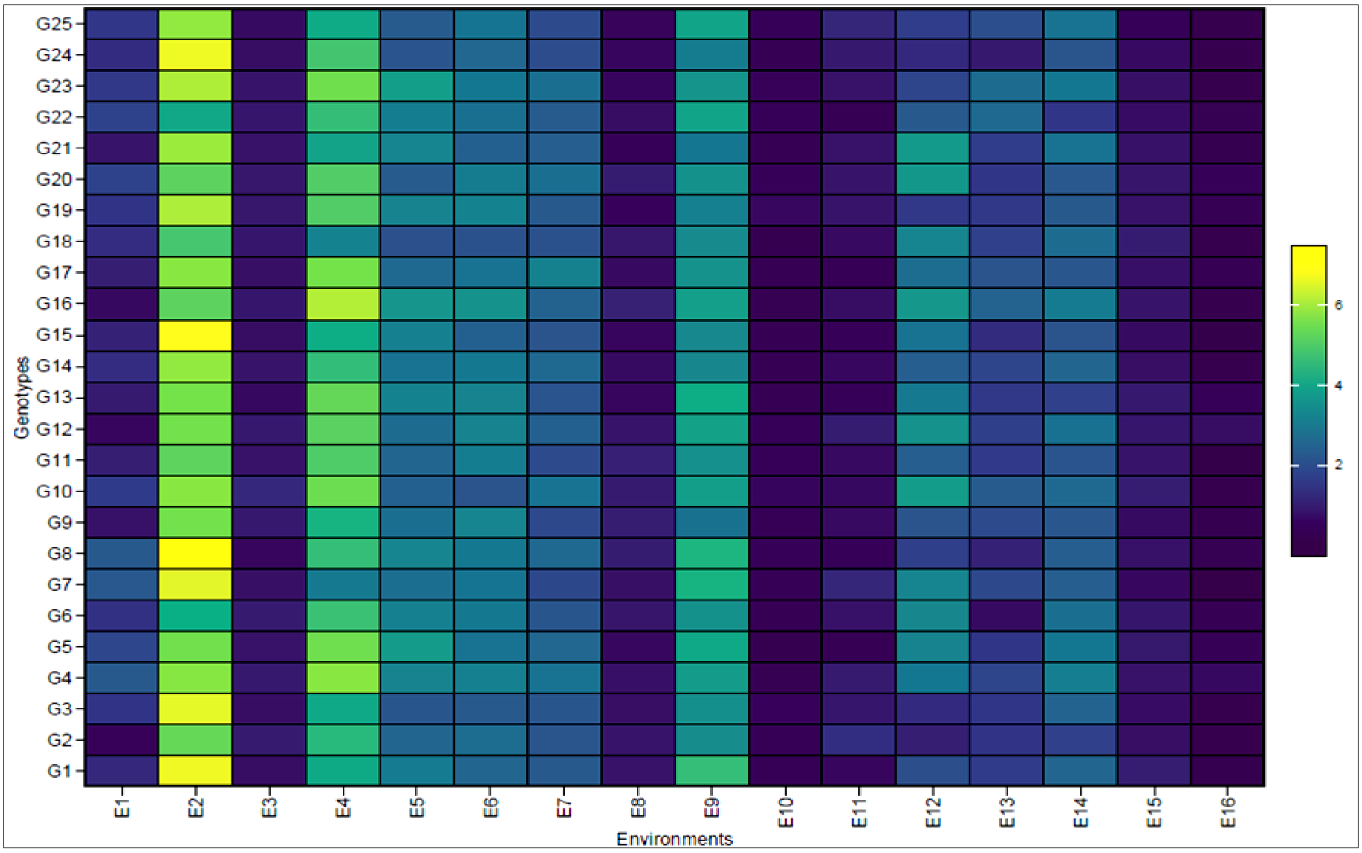

Fig. 1. Heat map showing environmental mean yield of 25 durum wheat genotypes across sixteen locations during three consecutive growing seasons to visually assess G × E interaction. G1 to G25 corresponds to the genotype listed in Table 1.; **E1**: AT21; **E2**: DYT21; **E3**: JSH21; **E4**: MCH21; **E5**: TST21; **E6**: AN21; **E7**: SEA21; **E8**: DYT22; **E9**: AN22; **E10**: MCH22, **E11**: AT21; **E12**: SEA22; **E13**: MCH23; **E14**: AT23; **E15**: DYT23; **E16**: SEA23.

Table 3. AMMI Analysis of variance for grain yield of 25 durum wheat genotypes in 16 environments

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Proportion (%)
ENV	15	2856.42	190.43	107.79	0***	77.91
REP(ENV)	32	56.53	1.77	4.71	1.74E-15***	1.54
GEN	24	29.65	1.24	3.29	2.4E-07***	0.80
GEN: ENV	360	217.52	0.60	1.61	3.21E-08***	5.93
PC1	38	69.58	1.83	4.88	0***	32
PC2	36	43.30	1.20	3.20	0***	51.9
PC3	34	25.19	0.74	1.97	0.0009***	63.5
Residuals	768	288.37	0.38			
Total	1559	3666.02	2.35			

*****:** highly significant at $p < 0.001$. **Df** :degree of freedom; **Sq** :square; **ENV:** environment; **REP:** replication; **GEN** :genotypes; **PC:** principal component.

In the same genotype, the yield ranged from one environment to another, i.e., for G1, the yield ranged from 1.24 $t.ha^{-1}$ in E1 to 6.68, 0.71 and 4.13 $t.ha^{-1}$ in E2, E3 and E4, respectively. The trend was the same in the other genotypes and the environment.

AMMI1 and AMMI2 biplot

Fig 2a of the AMMI1 biplot (mean GY vs PC1) illustrates the discrete behaviour of the environment. The vertical line for this biplot represents the grand mean value (2.14 $t.ha^{-1}$). Four classes (I to IV) can be used to explain the AMMI1 biplot (34). According to this classification, genotypes and environments with high (positive) interaction and high yield fall into class I; those with low (negative) interaction but high yield are in class II. Low interaction with low yield is represented in class III. Class IV includes genotypes with high interactions and low yield. In the AMMI1 biplot, high-yielding genotypes are displayed on the right side of the axis.

Genotypes and environments closer to the biplots' origin were stable and contributed minimally to the GEI. Conversely, genotypes and environments positioned farther from the origin significantly influenced the GEI. Twelve genotypes with a mean grain yield (GY) higher than the grand mean were identified: G1, G4, G5, G7, G8, G10, G12, G13, G16, G17, G20 and G23, with yield values of 2.16, 2.45, 2.33, 2.19, 2.25, 2.35, 2.28, 2.15, 2.42, 2.19, 2.23 and 2.34 $t.ha^{-1}$, respectively. G4, G17, G13 and G23 were more stable due to their proximity to the origin.

The lowest mean GY was observed in G2, G24, G18, G3 and G9 genotypes with 1.88, 1.91, 1.92, 1.96 and 1.99 $t.ha^{-1}$, respectively. The same trend was observed among the environments E2, E4, E9, E5 and E6, which showed the highest yield values of 5.77, 4.75, 3.67, 2.88 and 2.84 $t.ha^{-1}$, respectively. Meanwhile, E16, E10, E11, E8 and E15 showed the lowest mean yield, 0.31, 0.42, 0.74, 0.76 and 0.79 $t.ha^{-1}$, respectively.

The AMMI2 biplot uses the scores of the first two principal components, clearly depicting the GEI pattern (Fig. 2b). Genotypes with a significant PC1 score, indicating a high mean yield and small absolute PC2 scores are regarded as ideal genotypes. In contrast, genotypes with PC1 scores close to zero are considered stable (35).

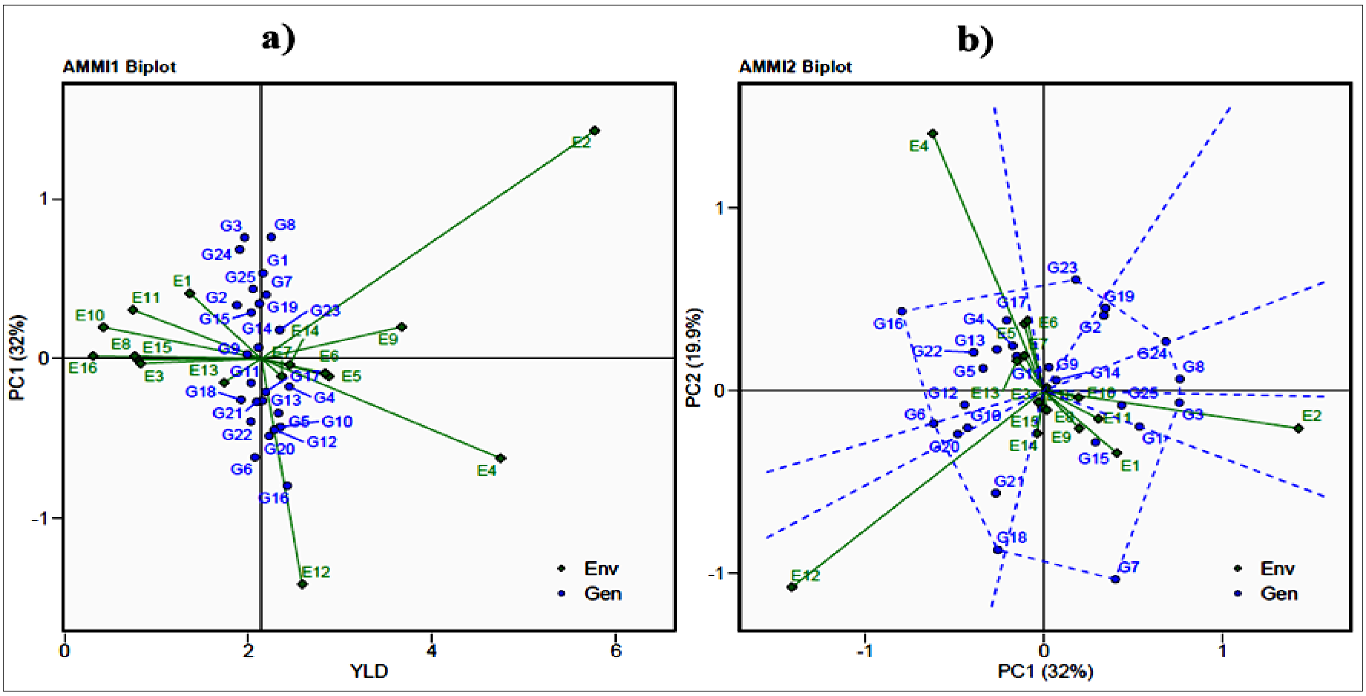

Fig. 2. a) The AMMI1 biplot between mean yield (t ha^{-1}) and PC1 represents the distribution of environments and genotypes based on interaction and additive effects. **b**) AMMI2, PC1 and PC2 plotted to obtain a polygon view. The genotypes in the centre of the polygon are the stable ones. **YLD**: Yield; G1 to G25 correspond to the genotypes listed in Table 1.; **E1**: AT21; **E2**: DYT21; **E3**: JSH21; **E4**: MCH21; **E5**: TST21; **E6**: AN21; **E7**: SEA21; **E8**: DYT22; **E9**: AN22; **E10**: MCH22, **E11**: AT21; **E12**: SEA22; **E13**: MCH23; **E14**: AT23; **E15**: DYT23; **E16**: SEA23; **Gen**: genotypes; **Env**: environment; **PC**: principal component.

The AMMI2 biplot aids in identifying genotypes adapted to specific environments within this study. It revealed that genotypes G16, G23, G24, G8, G3, G7, G18 and G6, positioned at the polygons' vertices, are the least stable due to their distance from the origin. In contrast, genotypes closer to the centre of the polygon are considered more stable. Additionally, environments E2, E4 and E12 showed the most extended vectors, indicating a strong discriminatory ability and a significant contribution to GEI.

GGE and Mean vs. Stability biplots

The utilization of the GGE biplot technique, as proposed by (32), facilitates the identification from different environments, the suitable genotypes based on their rank performance and evaluates test locations for representativeness. The sum of the two first principal components accounted for 51.41 %.

The genotypes closest to the lines' arrow indicated the highest average GY according to the GGE and mean vs. stability biplot. G16 showed the highest average yield among these genotypes, whereas G18 showed the lowest average. Based on this study, the mean stability biplot demonstrates that genotypes G16, G4, G5, G23, G17, G10 and G13 exhibited high mean GY. In contrast, genotypes G18, G7, G3 and G24 showed the lowest mean GY. The stability of genotypes was evaluated by observing the vector length (dotted line) between the average environment axis and each genotypes' position. According to this order idea, G4, G5, G16, G17 and G13 were identified to be the most stable genotypes, whereas G18, G7 and G3 were the least stable (Fig. 3b). Based on GY performance across all environments, the genotypes ranked as follows: G16 > G4 > G5 > G23 > G17 > G10 > G13 > G12 > G20 > G6 = G22 > G19 > G11 = G14 > G8 > G9 = G21 > G15 = G1 > G2 = G25 > G24 > G3 > G7 > G18.Genotypes G16, G4 and G23 exhibited a high-yielding genotype, although they demonstrated instability compared to genotypes G5, G17 and G13.

Ranking Genotypes, Which-Won-Where view of the GGE biplot and identification of mega-environments

The central position of the concentric circles is designated by a small arrow, indicating the ideal genotype. According to this concept, the genotype located in the centre is considered ideal and most suitable (36). In this case, G16 is closest to the centre. Consequently, this genotype was ideal. In contrast, G18 and G7 are located far from the circles' centre and are not ideal genotypes (Fig. 4a).

The which-won-where biplot identifies top-performing genotypes within specific environments (18). Based on the GY Which-Who-where analysis, the GGE biplot indicated that the genotypes G16, G23, G8, G24, G3, G7, G18 and G6 were positioned at the vertex of the six sectors. Among these genotypes, G16 was the most representative in 11 environments within the same sector, demonstrating its superior performance across various environments. This sector included genotypes G4, G5, G10, G12, G13 and G17, suggesting that these genotypes could perform similarly to G16. The genotypes G7, G6 and G18 located at the vertex have similar performance with G20, G22, G9, G11 and G21 in 1 environment. G4, G1 and G14 showed a best performance in 2 environments and G8, G19, G3, G2, G15 and G25 were also performed in 1 environment. Each of the six sectors identified in the biplot represents a mega-environment, respectively (Fig. 4b).

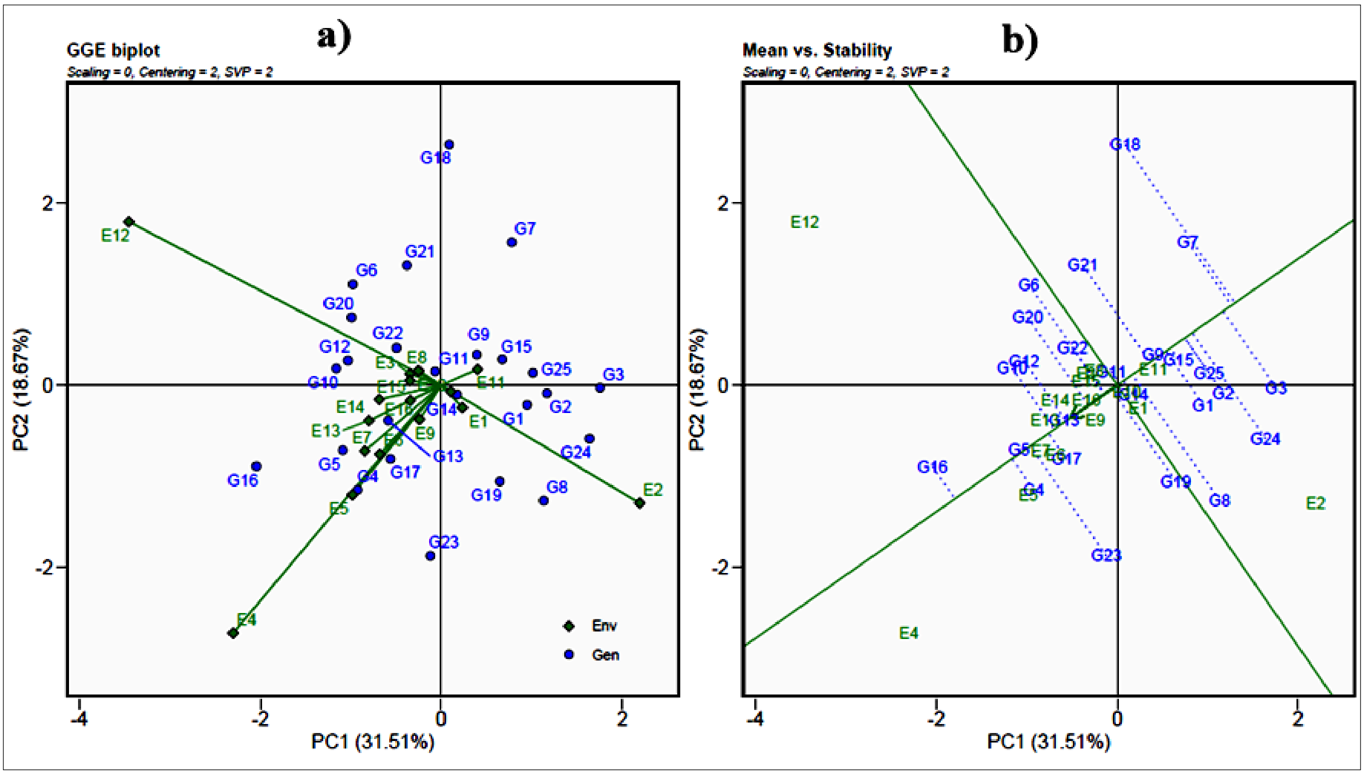

Fig. 3 a) Basic GGE plot between PC1 and PC2 showing the stability view and grouping of genotypes and environments between classes I-IV of the biplot. **b)** "Mean vs. Stability" view of GGE biplot considering mean yield of twenty-five durum wheat genotypes across sixteen different environments over three cropping seasons. G1 to G25 corresponds to the genotypes listed in Table 1.; **E1**: AT21; **E2**: DYT21; **E3**: JSH21; **E4**: MCH21; **E5**: TST21; **E6**: AN21; **E7**: SEA21; **E8**: DYT22; **E9**: AN22; **E10**: MCH22, **E11**: AT21; **E12**: SEA22; **E13**: MCH23; **E14**: AT23; **E15**: DYT23; **E16**: SEA23; **Gen**: genotypes; **Env**: environment; **PC**: principal component.

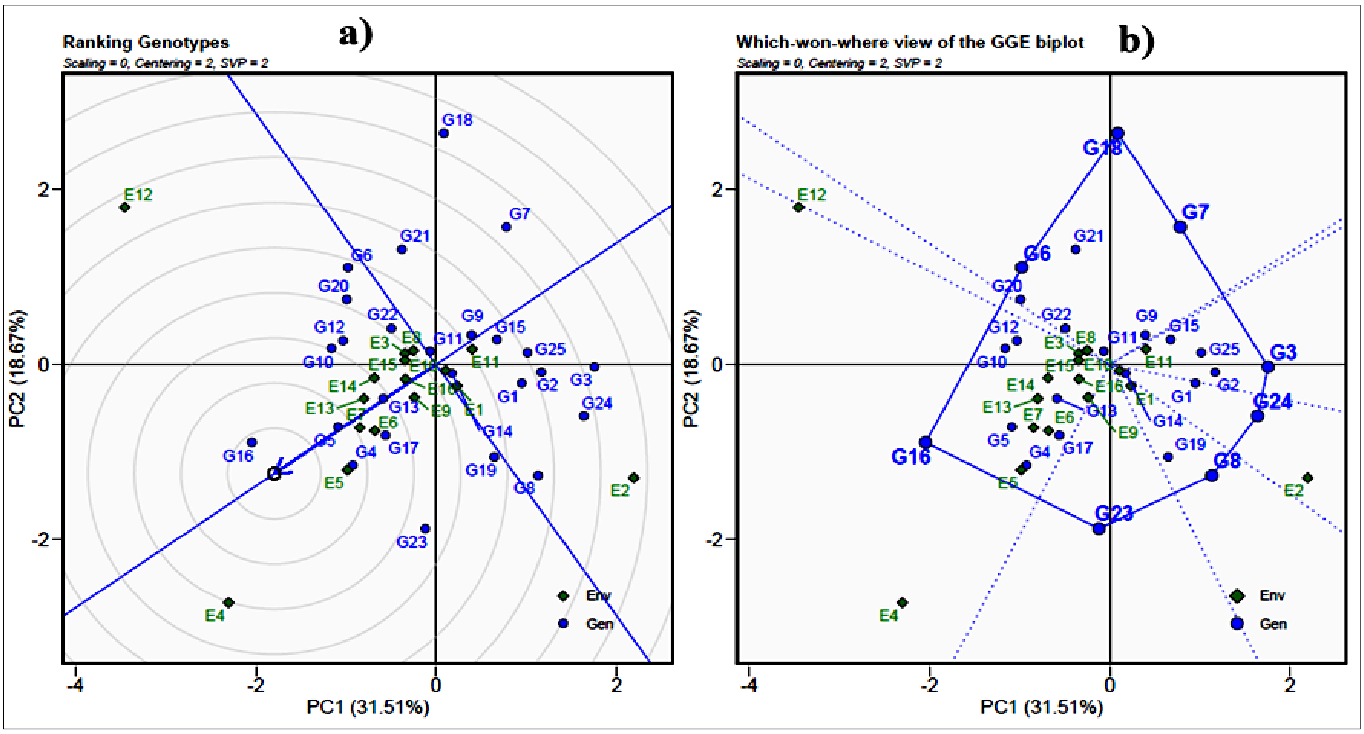

Fig. 4 a) Ranking of genotypes view of GGE biplot based on a hypothetical ideal genotype in the centre of concentric circles. **b)** Which-won-where GGE biplot showing 25 genotypes and 16 environments, the genotypes sharing the same sector with an environment are the most suitable genotypes for that specific environment in the same sector. G1 to G25 corresponds to a genotype in Table 1.; **E1**: AT21; **E2**: DYT21; **E3**: JSH21; **E4**: MCH21; **E5**: TST21; **E6**: AN21; **E7**: SEA21; **E8**: DYT22; **E9**: AN22; **E10**: MCH22, **E11**: AT21; **E12**: SEA22; **E13**: MCH23**;** **E14**: AT23; **E15**: DYT23; **E16**: SEA23; **Gen**: genotype; **Env**: environment; **PC**: principal component.

Ranking and Identification of Ideal Environment

A ranking environments biplot was created to identify the ideal environment for grain yield (GY), as shown in Fig. 5. This environment-focused biplot displays the Average Environment Axis (AEA), Average Environment Coordinate (AEC) and concentric circles. The ideal environment is located closest to the centre of the concentric circles. In this study, environment E4 emerged as ideal for GY, as it was closest to the centre and had the smallest angle with the AEA, allowing genotypes to express their genetic potential fully. This finding supports E4 as an optimal environment for developing and evaluating durum wheat varieties. The other environments were ranked by their proximity to the ideal, following this order: E4 > E5 > E7 > E6 > E13 > E14 > E9 = E16 > E15 > E3 > E8 > E1 = E10 > E11 > E12 > E2 (Fig. 5a).

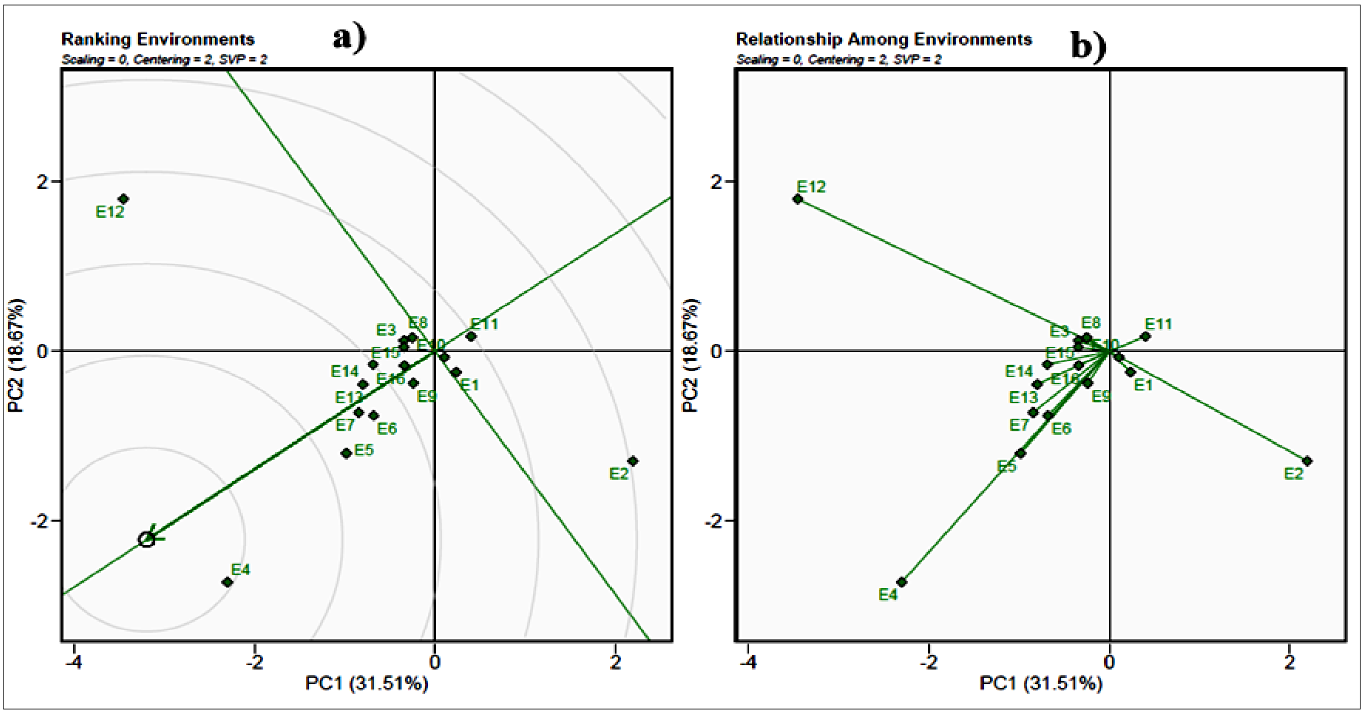

Fig. 5. a) Ranking of environments view of GGE biplot based on a hypothetical ideal environment in the centre of concentric circles. **b)** Relationship between environments GGE biplot shows the test environments' correlation. **E1**: AT21; **E2**: DYT21; **E3**: JSH21; **E4**: MCH21; **E5**: TST21; **E6**: AN21; **E7**: SEA21; **E8**: DYT22; **E9**: AN22; **E10**: MCH22, **E11**: AT21; **E12**: SEA22; **E13**: MCH23; **E14**: AT23; **E15**: DYT23; **E16**: SEA23; **PC**: principal component.

Selection of Superior Genotypes

Table 4 represents the ranking of the 25 durum wheat genotypes based on their mean GY, ASV value and GSI. Genotypes with an ASV value closer to zero are considered more stable, while those farther from zero are less stable. According to the ranking based on ASV, the first four positions are occupied respectively by G14, G9, G11 and G4, while the last four stable genotypes were G16, G8, G3 and G7 due to their highest AS value. Additionally, based on GY making, G4, G16, G10 and G5 occupied the first four places. The GSI was calculated according to ASV and GY rankings, identifying genotypes with the lowest GSI values as the most stable and high-yielding. Based on GSI, the top five genotypes were G4, G5, G23, G14 and G17, while the lowest-ranked genotypes with the highest GSI value were G24, G3, G18, G2 and G6.

Discussions

Identifying high-yielding and stable genotypes across diverse environments is essential for any breeding program, particularly in the face of climate change, to support global food security. This study aimed to assess the performance of durum wheat genotypes across varied environmental conditions representing Moroccos' primary durum wheat-growing regions. The objective was to identify genotypes that produce high yields and maintain stability, enabling the recommendation of suitable varieties for each environment and mega-environment. Thus, analyzing and observing GEI in multi-environment trials is crucial for evaluating, selecting and recommending optimal genotypes (37).

The combined analysis of variance showed a significant difference among genotypes, environments and GEI at $p < 0.0001$. This revelation allows us to deduce that all components govern the yield. Still, the environmental effect controls the major part of variation, with 77.91 % of variation versus 0.80 % for genotypic variation. GEI contributes 5.4 % to this variation, suggesting that ecological and climatic conditions are the limits of yield. The large percentage of the environmental effect (77.91 %) indicated the diversity of these environments, causing the greatest variation in grain yield among durum wheat genotypes. According to previous research, the diversity of these environments caused the most significant variation in the grain yield of durum wheat genotypes (38, 39). These findings are supported by previous research, which indicates that the high percentage of the sum of squares attributed to the environment suggests that the test environments were highly diverse, significantly impacting yield performance and contributing to most of the variation in grain yield (40, 41). Unpredictable environmental conditions are a significant constraint for breeding superior and widely adapted durum wheat genotypes.

The average yield was 3.21 $t.ha^{-1}$ in the first year, 1.86 $t.ha^{-1}$ in the second year and 1.32 $t.ha^{-1}$ in the third year, reflecting variations in climatic conditions. This is due to favourable or unfavourable environmental conditions during the three years, mainly drought and poor rainfall distribution during the plants' development cycle. The high yields in environments with good rainfall (4.73 $t.ha^{-1}$ in MCH21) and low yields in environments with low rainfall (0.42 $t.ha^{-1}$ in MCH22 and 1.73 $t.ha^{-1}$ in MCH23) demonstrated that rainfall is a determining factor for the GY of the durum wheat genotypes. From this perspective, (4) reported that the variation in wheat yield strongly depends on environmental conditions. Our studys' significant correlation between rainfall and yield confirmed these hypotheses. In the same order, (18, 37) reported that the distribution of precipitation is determined during the growth stages. Therefore, it is necessary to optimize the sowing dates to benefit as much as possible from rainfall and ensure a good distribution of water resources by providing additional efficient irrigation. Sowing date is a crucial factor affecting crop growth and yield, with an optimal sowing date positively influencing grain yield through improved adaptation to physiological, phenological and environmental conditions. Proper management of sowing date, variety and environmental factors can increase wheat yield by 10 to 80 % (38, 39).

Table 4. Ranking of 25 durum wheat genotypes based on yield, ASV and GSI across 16 environments

Genotypes	Mean yield (t ha^{-1})	YLD-R	ASV	ASV-R	GSI	GSI-R
G1	2.16	11	0.88	18	29	13
G2	1.88	25	0.68	11	36	15
G3	1.96	22	1.22	23	45	17
G4	2.45	1	0.37	4	5	1
G5	2.33	5	0.56	8	13	2
G6	2.07	16	1.01	20	36	15
G7	2.19	9	1.22	22	31	14
G8	2.25	7	1.23	24	31	14
G9	1.99	21	0.14	2	23	9
G10	2.35	3	0.72	15	18	7
G11	2.03	19	0.31	3	22	8
G12	2.28	6	0.72	16	22	8
G13	2.15	12	0.48	5	17	6
G14	2.11	14	0.13	1	15	4
G15	2.03	18	0.54	7	25	10
G16	2.42	2	1.35	25	27	11
G17	2.19	10	0.51	6	16	5
G18	1.92	23	0.97	19	42	16
G19	2.12	13	0.72	14	27	11
G20	2.23	8	0.81	17	25	10
G21	2.09	15	0.71	13	28	12
G22	2.03	20	0.67	9	29	13
G23	2.34	4	0.67	10	14	3
G24	1.91	24	1.13	21	45	17
G25	2.05	17	0.71	12	29	13

The AMMI model combines variance and principal component analysis with fixed effects without relying on external data or additional structure for environments and genotypes. It helps identify genotypes that perform consistently across diverse environments and environments that significantly impact specific genotypes. The AMMI model can also reveal genotype-by-environment interaction patterns and assess genotype stability across various environments (45, 46).

The results of the AMMI analysis demonstrated that the GEI and environment accounted for the majority, with 83.3 % of the variation. This result aligns with the findings of (47 - 49), who utilized the AMMI model to analyze the GEI and reported that the GEI explained 84.3 and 82.9 percent of the total variation in yield, respectively.

PC1 reflects the adaptability of genotypes and is strongly correlated with performance, while PC2 represents stability (20). When such interactions occur, PC1 and PC2 account for at least 50 % of the total variation (50). In this study, the two PCs explain 51.9 % of the total variation, suggesting that other factors, including drought, rainfall distribution during the stage of the plant cycle and sowing date, may also impact the yield.

The GGE biplot analysis enables visualization of the relationship between genotypes and environments, identifying genotypes that perform well across various environments. Combining two key sources of variation-genotype and G × E-the GGE biplot facilitates the analysis of mega-environments, evaluation of genotypes and discrimination of environments in graphical form. This information guides breeding and selection decisions to develop cultivars suited to diverse environments (18, 19).

Identifying mega-environments is the optimal approach to selecting genotypes with stable performance, as it enhances understanding complex genotype-by-environment interactions within a specific region. Additionally, breeding genotypes specifically adapted to distinct mega environments helps develop environment specific cultivars (51). Research indicates mega environments as locations yield similar and repeatable genotype responses over time (37). In this study, five distinct mega-environments were identified. The largest, Mega environment I, included eleven locations (E3, E4, E5, E6, E7, E9, E12, E13, E14, E15 and E16), followed by Mega environment II, which comprised two locations (E2 and E10). Environments E1, E11 and E8 correspond to Mega environments III, IV and V, respectively.

The generation by the Which-Won-Where polygon GGE biplot of the five mega-environments may be explained by the difference in cropping season conditions. A more significant environmental effect generates more mega-environments and, therefore, widely distributed varieties among the mega-environments. What must be raised is that the recent varieties, unlike the old ones, perform well, which can be attributed to the selection progress. Mediterranean environments are generally known to be associated with droughts and high temperatures. Research suggests that selection strategies implemented in recent decades have effectively reduced the GEI effect, facilitating the selection of genotypes with more excellent stability. As a result, newer varieties exhibit better adaptability to environmental conditions than older ones (52). Yield stability refers to a genotypes' ability to maintain a consistent yield across varying environments, a key trait for breeding programs. Genotypes with high, stable yields are ideal for cultivar selection or as parents in breeding crosses (53).

Genotype performance and stability fall into three categories: (1) genotypes that are broadly adapted, with high and stable yields; (2) genotypes that are specifically adapted, showing high mean yield but low stability; and (3) genotypes that are poorly adapted, with low yield and stability (21). Based on the analyses, G16 was identified as "ideal," while G4, G5, G14, G17 and G23 were deemed "desirable" due to their consistent performance, low environmental interaction and relative stability.

Conclusion

Durum wheat is one of the oldest cereal crops cultivated in the Mediterranean Basin, especially in Morocco. The variance analysis displayed highly significant differences between genotypes, environments and GEI, with AMMI analysis indicating that environmental factors accounted for most of the yield variation. Based on G × E analysis, genotypes G16, G4, G5, G14, G17 and G23 were identified as high-yielding and stable across different environments.

Identifying mega-environments with optimal genotypes can significantly enhance production in each area, promote food security and increase farmers' revenue. Yield improvements of up to 40-50 % can be achieved by identifying stable, high-yielding genotypes. Additionally, accelerating the identification and use of genes linked to grain yield can speed up the development of new cultivars with enhanced yield potential and other desirable traits.

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Authors' contributions

MH, SB, GD and MT conceptualized the research problem. SB, GD, MH and MT helped in methodology. MH, SB and MT helped in the validation of research. MH and FG helped in data analysis. MH and MA helped in experimenting. MH contributed to data curation and also participated in writing the original draft. MH wrote and reviewed the manuscript. SB GD, RH and MT supervised the research. All authors have read and agreed to the manuscript.

Compliance with ethical standards

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Ethical issues: None

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