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Sustainable wheat subspecies mixtures production by evaluating morphological traits and stability analysis of different varieties in different environments in Jordan

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ABSTRACT

Climate change and water scarcity present significant challenges to food security in arid and semi-arid regions, such as Jordan. Grains—particularly wheat—are essential for nutrition and national food security. This study addresses sustainable wheat production strategies under semi-arid conditions, focusing on the utilization of morphological characteristics through targeted breeding programs. Assessing genetic diversity is a critical prerequisite for evaluating population adaptation to novel environmental conditions. This study aimed to evaluate the morphological traits and yield stability of seven certified wheat (*Triticum aestivum* L.) varieties—ACSAD65, Ammoun, Cham1, Dair Alla6, Hourani, Mixture, and Um Qais—across three contrasting environments at Maru, Mushager, and Rabbah. These sites represent diverse agro-ecological zones within the semi-arid landscape of Jordan. The experiment was conducted using a randomized complete block design (RCBD) in a 3×7 factorial split-plot arrangement, where the three locations served as main plots and the wheat varieties as subplots. Results indicated that both location and growing season significantly affected yield and its components. The variety Um Qais exhibited the highest grain yield, while the mixture showed poor performance. Among the locations, Maru demonstrated superior performance in terms of biological yield, grain yield, straw yield, and harvest index, followed by Mushager and Rabbah. According to GGE biplot analysis, Um Qais emerged as the ideal genotype for grain yield, achieving the highest mean performance across all locations. These findings offer valuable insights for policymakers, agricultural researchers, and farmers by identifying high-yielding and stable wheat varieties that are adapted to local semi-arid environments.

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1. INTRODUCTION

Climate change has emerged as a global challenge with significant and increasing impacts on global food security (Al Tawaha et al., 2025; Ali et al., 2020; Ali et al., 2019; Choukri et al., 2023; Michael, 2020; Sulaeman et al., 2023). Its effects are particularly severe in arid and semi-arid regions such as Jordan, where changes in temperature and precipitation patterns are altering water availability and cropping conditions (Chandio, Akram, et al., 2020; Chandio, Jiang, et al., 2020). These shifts contribute to increased frequency of droughts, fluctuations in seasonal rainfall, and higher atmospheric CO_2 concentrations, all of which directly affect crop growth and productivity. The agricultural sector is particularly vulnerable, with cereal production experiencing reduced yields due to combined heat and water stress (Dixit et al., 2018; Kanaoujiya et al., 2025; Porter et al., 2014; Shawaqfeh et al., 2025). In Jordan, wheat is cultivated across diverse agro-ecological zones—ranging from the relatively humid northern highlands (e.g., Maru, ~431 mm rainfall; clay soil) to drier central and southern regions (e.g., Mushager and Rabbah, 400 mm and 350 mm rainfall, respectively; clay loam and silty clay soils). These variations in climatic and edaphic conditions necessitate the evaluation of wheat varieties

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under multiple environments to ensure stable and resilient crop performance (Dixit et al., 2018; Kanaoujiya et al., 2025; Porter et al., 2014; Shawaqfeh et al., 2025).

The main cereal crops are wheat, corn, and rice; therefore, by 2050, a 70–100 percent increase in grain food supply is required to feed the projected global population of 9.8 billion people (Al-Tawaha et al., 2022; Mesterházy et al., 2020). Wheat is particularly critical for food security, as it serves as a primary source of calories and nutrition for billions. It contains 75–80% carbohydrates, 9–18% protein, essential vitamins—especially B-complex—fiber, calcium, iron, and various micronutrients, making it a staple in many diets. In Jordan, wheat is deeply embedded in daily consumption habits, commonly used in products such as bread, pasta, sweets, and other staple foods. According to the Ministry of Industry and Trade (MIT, 2023), the country's average monthly wheat consumption is approximately 90,000 tons. Beyond its grain value, wheat straw also plays an important role in livestock feeding systems, particularly in smallholder mixed farming operations. Despite its significance, domestic wheat production in Jordan meets only a fraction of the demand due to challenges such as erratic rainfall, limited high-yielding cultivars, and soil fertility constraints. These limitations underscore the need for evaluating the performance and stability of certified wheat varieties across diverse environments—an effort that this study undertakes.

Jordan is a dry region with little rainfall, and high temperatures have a negative physiological effect on wheat and limit growth yield. Therefore, wheat is the crop most affected by climate change, as it is a rain-fed crop for both local farmers and Bedouins in places where rainfall exceeds 350 mm. Singh et al. (2011) reported that even a 10 °C increase in average temperature in March and April results in a seven-day reduction in wheat harvest and a yield of about 400 kg per hectare. Asseng et al. (2015) reported that global wheat production is estimated to decrease by 6% for each additional °C increase in average temperature. Furthermore, wheat quality is influenced by both genotypic and environmental factors (Beres et al., 2020; Johansson et al., 2020; Li & Tao, 2022; Ljubičić et al., 2021; Osman et al., 2021). In the past 20 years, Jordan has supported the adoption of technologies among farmers through numerous measures, including using better seed varieties, agricultural techniques, and water harvesting techniques (Momany, 2001). It is known that selecting ideal wheat varieties with optimal characteristics through morphological and agronomic evaluation for each area is an important strategy to increase wheat production and maintain Jordan's food security. Morphological traits are crucial for determining essential traits that can be used in breeding programs (Khadka et al., 2020) and sustainability strategies for the ideal variety for each location with specific environmental conditions.

Additionally, morphological trait descriptors are displayed as the presence/absence of character status to distinguish accessions during germplasm evaluation (Güngör et al., 2024). The assessment of genetic diversity is an essential prerequisite for studying the adaptation of populations to new environmental conditions and, therefore, for the selection of new varieties (Tékeu et al., 2017). This study aimed to evaluate the certified wheat varieties with their mixture and measure their suitability for implemented areas under local rainfall conditions, under the impact of climate change. The evaluation focused on key agronomic traits such as growth, yield, and harvest index (HI) across three growing seasons and diverse agro-ecological zones. Genotype evaluation is essential because wheat performance varies significantly across environments due to interactions between genetic potential and local climatic and soil conditions. In Jordan, despite the availability of certified wheat varieties, yield variability remains high and often falls below the genetic potential due to erratic rainfall, heat stress, and soil constraints. Previous studies have reported inconsistent performance of the same genotype across different locations and seasons, making it difficult for farmers to select varieties with stable and high productivity. Therefore, multi-environment trials (METs) are a vital tool to identify wheat varieties that combine high yield with adaptability and resilience to local stresses. This approach not only helps breeders select superior lines but also provides farmers with reliable choices tailored to specific environmental conditions. In light of Jordan's limited water resources and growing demand for wheat, the identification of stable, climate-resilient varieties is crucial for enhancing national food security.

2. MATERIAL AND METHODS

2.1. Site description

The field experiment was conducted at three stations of the National Agriculture Research Center (NARC): Maru Agriculture Station (32.55°N, 35.85°E, elevation 620 m), Mushager Agriculture Research Center (31.77°N, 35, 77°E, altitude 790 m) and Rabbah Agricultural Research Center (31°16' N, 35° 45' E, altitude 920 m) during three seasons (2015-2016, 2016-2017 and 2017-2018) in Jordan.

2.2. Soil properties

Prior to cultivation, soil samples were randomly collected from the three experimental sites to analyze key physical and chemical properties, including soil texture, pH, electrical conductivity (EC), total nitrogen content, and available phosphorus and potassium levels (expressed in parts per million) (Table 1). Additionally, the average annual rainfall for each location was recorded: Maru receives approximately 431 mm, Mushager around 400 mm, and Rabbah about 350 mm per year.

Table 1: The soil and environmental characteristics of experimental sites

Location	Soil Texture	pH	EC (dS/m)	Nitrogen (%)	Phosphorus (ppm)	Potassium (ppm)	Rainfall (mm)
Maru	Clay	7.7	0.53	0.085	3.8	401	431
Mushager	Clay Loam	7.9	0.5	0.046	1.45	433.3	400
Rabbah	Silty Clay	7.8	0.51	0.487	4.1	487.2	350

Table 2. The description of the varieties used in this study.

No	Name	Type	Source	Year of release
1	ACSAD65	Durum	CIMMYT	1988
2	Dair Alla6	Durum	Jordan	1974
3	Hourani	Durum	Jordan	1976
4	Cham1	Durum	ICARDA	1988
5	Um Qais	Durum	ICARDA	2004
6	Ammoun	Bread	ICARDA	2004

2.3. Plant materials

Certified wheat seeds representing Jordanian cultivars were sourced from the National Seed Bank at the National Agricultural Research Centre (NARC), Jordan. The study included five durum wheat (*Triticum turgidum* subsp. *durum*) cultivars—ACSAD65, Dair Alla6, Hourani, Cham1, and Um Qais—and one bread wheat (*Triticum aestivum*) cultivar, Ammoun (Table 2). Additionally, a composite treatment consisting of a mixture of all six cultivars was evaluated. Detailed descriptions of the wheat varieties used are provided in Table 2.

2.4. Experimental Design, Treatments and Layout

The field study was conducted over three successive growing seasons (2015–2016, 2016–2017, and 2017–2018) using a randomized complete block design (RCBD) in a split-plot arrangement with a 3 × 7 factorial combination. The main plot factor included three experimental locations representing different agro-ecological zones: Maru, Mushager, and Rabbah. The sub-plot factor consisted of seven wheat genotype treatments: five durum wheat varieties (ACSAD65, Dair Alla6, Hourani, Cham1, and Um Qais), one bread wheat variety (Ammoun), and a mixture of all six varieties. Each treatment was replicated twice per block.

The total experimental area covered 250 m². Each individual plot contained six rows, each 6.6 meters in length, with 0.25-meter spacing between rows. A 1-meter buffer zone separated adjacent plots to prevent treatment interference. Within each replication, the seven varieties were randomly assigned to sub-plots, forming a complete factorial structure under each location treatment.

2.5 Site Preparation and Crop Management

The land was managed under a wheat-legume crop rotation system to maintain soil fertility. Soil preparation was conducted using a duck-foot plow in March and October of each year. Prior to sowing, the soil surface was leveled, and planting furrows were opened automatically to standardize planting depth and spacing across the site. Sowing was performed immediately following soil preparation, with each variety planted in its designated plot and replication layout as described. The consistent layout and treatment randomization ensured statistical robustness and minimized spatial variability.

2.6 Weed Control and Fertilization Practices

Weed management was implemented through the application of selective broadleaf and narrow-leaf herbicides at a rate of 1000 mL ha^{-1}, applied one week before sowing. This ensured a clean seedbed and minimized early-season competition. Fertilization was conducted in two stages after crop emergence. Di-ammonium phosphate (DAP) and urea (46% nitrogen) were used to supply essential macronutrients, particularly nitrogen and phosphorus, required for optimal crop growth and yield development. Fertilizer application rates were consistent across all treatments to isolate the effects of genotype and location.

2.7. Yield and yield components

Measurements taken during three seasons included days to heading (days), physiological maturity(days), plant height(cm), biological yield (g m^{-2}), grain yield (g m^{-2}), and Harvest index (HI) for the seven wheat varieties at the three experimental sites.

2.7.1. Days to heading

Day to heading (day) was counted as the number of days between emergence and the appearance of 50% of the wheat spike from the leaf sheath and the appearance of the barley awn above the collar of the flag leaf in 50% of the plants in the plot.

2.7.2. Day of maturity

The day of maturity (day) was counted as the number of days between emergence and the day when all the plants in the plot became yellow.

2.7.3 Plant height

Plant height (cm) was measured from the plant's ground level to the end of its tallest leaves to the end of the spike without the awns.

2.7.4. Biological yield

Biological yield (g.m^{-2}) was calculated using the average straw and grain weight of a 3 m^2 sample selected randomly from each plot.

2.7.5. Grain yield

Grain yield (g.m^{-2}) was calculated using the average grain weight of a 3 m^2 sample picked randomly from each plot, and measured after threshing and washing, and straw yield (g m^{-2}) was calculated by dividing grain yield by biomass yield.

2.7.6. Harvest index

The harvest index was calculated by dividing the grain yield by the biological yield and multiplying by 100 to get its value in percentage. The seeds were harvested per plot at maturity and sun-dried to 12% moisture content, threshed, and five hundred seeds were randomly picked/plot and weighed, then multiplied by two to get 1000 seed weight(g).

2.8. Statistical analyses

The correlation analysis was performed to determine the relationship between phenological traits (days to heading, days to physiological maturity, grain filling period, plant height, biological, grain and straw yield, harvest index, and 1000 kernel weight) and experimental site, wheat varieties, and growing seasons. Data was analyzed using combined analysis for multi-environment trials (METs). Data observed were subjected to the Analysis of Variance and the Least Significant Difference test using the Studio 4.3 version. GGE Biplot was done using the metan package in R version 4.1.0.

Table 3. Mean square for wheat varieties for experimental locations Maru, Mushager, and Rabbah during growing seasons from 2016 to 2018

Source of Variation	DF	Days to Heading	Days to Maturity	Plant Height	Biomass Yield	Grain Yield	Straw Yield	Harvest Index	1000KW
V	6	60***	74***	805***	2931950	445653*	2373262*	49.8	170.4***
R	1	70***	142***	62	305345	196151	12038	58.6	9.5
Y	2	744***	1006***	2244***	100748032***	8917889***	50770746***	187.7 **	1936.0***
L	2	11482***	7184***	12375***	331210932***	35560994***	149907255***	1376.4***	351.7***
V*R	6	0	2	38	2345022	258128	1119835	20.7	11.4
V*Y	12	15***	20***	169***	1698821	206661	1201928	33.4	12.2
R*Y	2	23***	17***	13	2949731	1010134**	550150	201.7**	34.5*
V*L	12	13***	33***	71	1045362	244933	430898	39.2	12.3
R*L	2	39***	18***	12	2838787	214637	1785700	12.7	23.5
Y*L	4	951***	2269***	6054***	275361983***	19115732***	175034635***	2908.5***	160.3***
V*R*Y	12	1	1	36	980960	181550	569103	43.0	7.2
V*R*L	12	2	2	31	891089	128128	493508	50.9	5.3
V*Y*L	24	7***	20***	66*	1887685	205366	1395392	60.7	17.8*
R*Y*L	4	2	10**	72	4968575*	347091	2752146*	3.4	4.0
V*R*Y*L	24	1	1	40	1081690	213685	554684	45.7	3.8
Error	56	1	2	37	1583074	143666	956612	37.4	7.3
h (%)		95.16	92.31	87.37	22.12	41.20	33.05	9.95	88.16

Notes: V=varieties, R= Replication, Y= Year, L= Location, *significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$ level

Heritability in this study was calculated using Equation 1 (Johnson et al., 1955).

$$h^2b = (\sigma^2g / \sigma^2ph) \times 100 \quad [1]$$

3. RESULT

3.1. Analysis of variance of wheat yield and traits

Table 3 summarizes the ANOVA results for growth and yield parameters as influenced by wheat varieties (V), location (L), and growing season (Y). Significant differences were observed in the interaction of VLY for days to heading, days to maturity, plant height, and 1000-kernel weight. The interaction between V and Y significantly influenced days to heading, days to maturity, and plant height. Additionally, VL interactions significantly affected days to heading and days to maturity. The YL interaction significantly impacted days to heading, days to maturity, biomass yield, plant height, straw yield, and harvest index. Variety (V) alone showed a strong effect ($P \leq 0.001$) on days to heading, days to maturity, plant height, and 1000-kernel weight and a moderate effect ($P \leq 0.05$) on grain and straw yields.

3.2. Effect of different wheat varieties and locations on days to heading and maturity, and plant height

Figures 1 and 2 demonstrate clear differences in days to heading and days to maturity across wheat varieties and experimental locations. Among the varieties, Dair Alla6 and Hourani consistently exhibited a longer time to reach heading, whereas *ACSAD65* was notably earlier, reflecting variation in genetic growth cycles. Similarly, *Ammoun* matured faster than most varieties, while Dair Alla6, Um Qais, Mixture, and Hourani had relatively longer durations to maturity. The environmental effect is also prominent: wheat grown in Maru headed and matured significantly earlier than in Mushager and Rabbah, suggesting the influence of regional climate and soil conditions on phenological development.

Figure 3 highlights significant variation ($p < 0.001$) in plant height among varieties. Hourani recorded the greatest height, followed by Um Qais and Mixture, indicating their vigorous vegetative growth potential. In contrast, Dair Alla6 exhibited the shortest stature, potentially reflecting its adaptation to more compact growth habits. Environmental conditions also played a key role in plant height, as shown in Figure 4. Wheat grown at Maru was substantially taller than at Mushager and Rabbah, with increases of 28% and 27%, respectively. This suggests that Maru's favorable rainfall and soil characteristics supported more robust vegetative growth.

3.3. Effect of different wheat varieties and locations on yield component

Table 4 reveals that Um Qais and Cham1 varieties have the highest biological yield (kg ha^{-1}) with values of 6330.08 and 6524.39, respectively. In contrast, the Um Qais genotype had the highest grain yield (1909.15 kg ha^{-1}), followed by ACSAD65, Dair Alla6, Ammoun, Cham1, Hourani, and Mixture. The grain yield for Um Qais was higher than the mixture, Hourani, and Cham1 by 20%, 17.5%, and 15.2% respectively (Table 4). For the straw yield, the Cham1 genotype achieved the highest value (4712.85 kg ha^{-1}), while the Um Qais genotype had the highest harvest index. Regarding 1000kernel weight (g), Dair Alla6 had the highest by 24.4% compared to the Ammoun genotype. The result for yield in this study based on year was contrary to the wheat yield statistics for Jordan from USDA in the season 2015/2016 to 2017/2018 seasons, it was reported that 1.3 T ha^{-1}, 1.3 T ha^{-1}, and 1.0 T ha^{-1} were Jordan wheat yield for 2015/2016, 2016/2017 and 2017/2018 respectively.

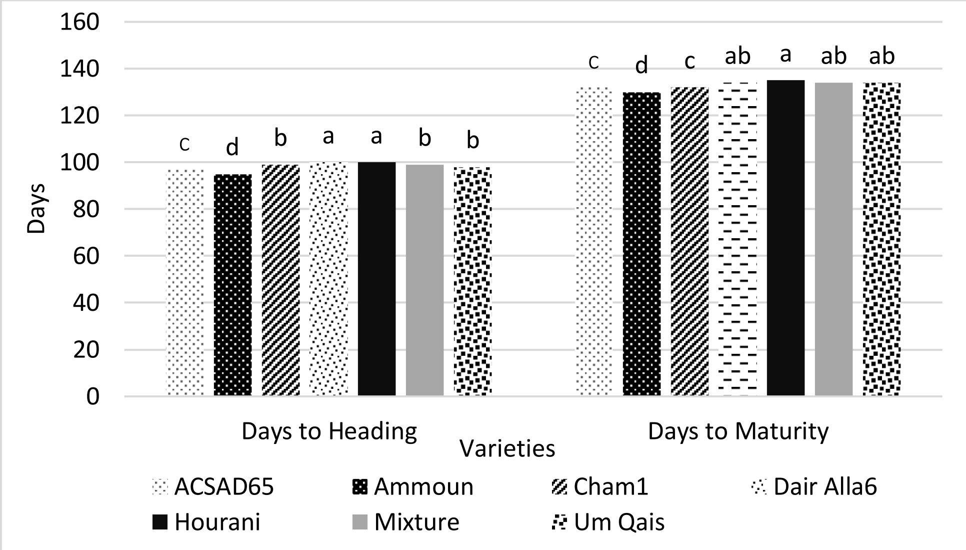


Figure 1. Effects of wheat varieties on days to heading and days to maturity. Means for each treatment followed with the same letter are not significantly different at P-value 0.05 using LSD

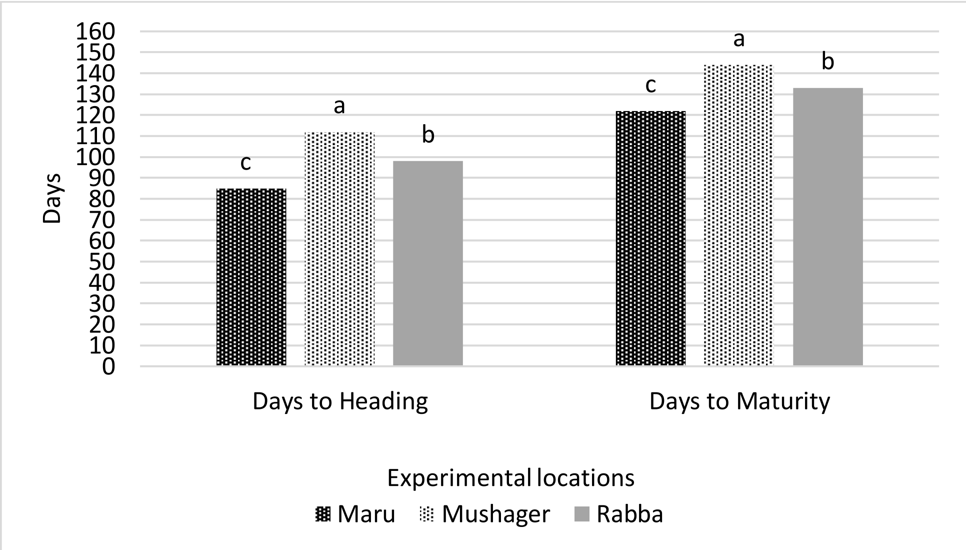


Figure 2. Effects of the experimental locations on days to heading and days to maturity of wheat. Means for each treatment followed with the same letter are not significantly different at P-value 0.05 using LSD

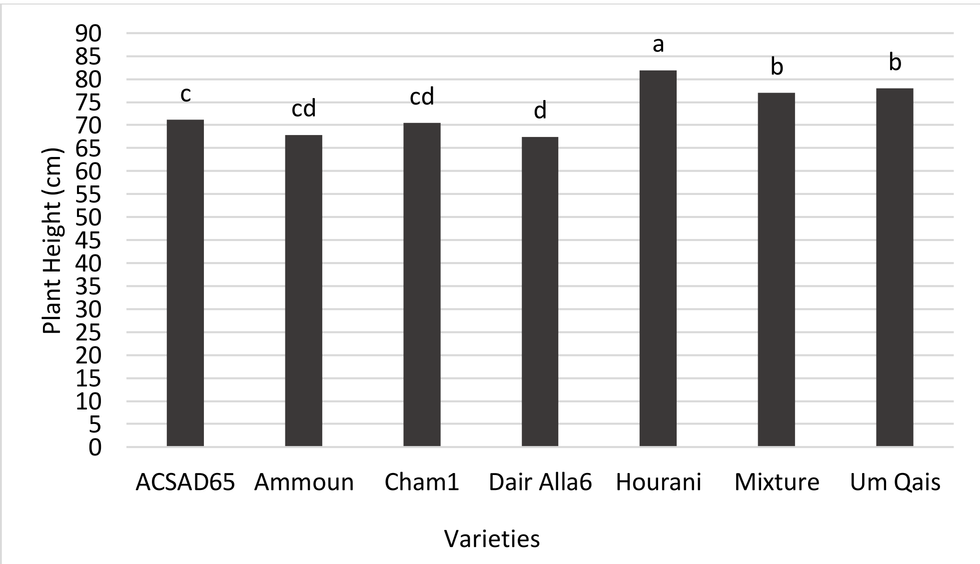


Figure 3. Effects of wheat varieties on the plant height trait. The means for each treatment followed by the same letter are not significantly different at a P value of 0.05 using LSD

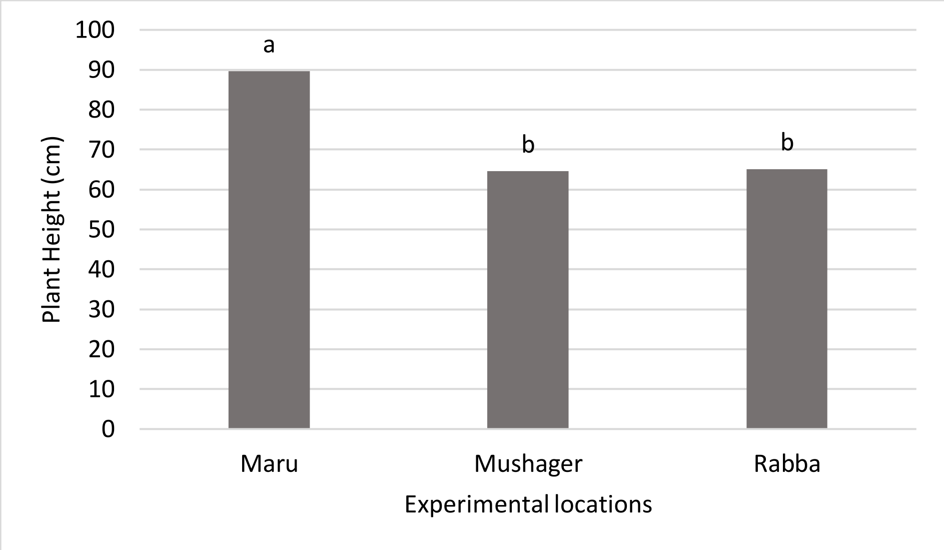


Figure 4. Effects of experimental locations on plant height. The means for each treatment followed by the same letter are not significantly different at a P value of 0.05 using LSD

Table 4. Effect of varieties factor on biological, grain, and straw yield (kg.ha^{-1}), harvest index, and 1000 kernel weight (g)

Varieties	Biological Yield (kg.ha^{-1})	Grain Yield (kg.ha^{-1})	Straw yield (kg.ha^{-1})	Harvest index	1000 Kernel weight (g)
ACSAD65	5945.46ab	1753.01ab	4192.46abc	27.39ab	36.54b
Ammoun	5506.00b	1636.08bc	3869.92 c	28.39a	29.95e
Cham1	6330.08a	1617.23bc	4712.85 a	27.05ab	32.03d
Dair Alla6	5844.31ab	1699.23abc	4145.08bc	26.68ab	39.63a
Hourani	6139.77ab	1574.69bc	4565.08ab	25.84ab	36.14bc
Mixture	5912.12ab	1512.19 c	4399.92 abc	24.36ab	35.54bc
Um Qais	6524.39a	1909.15 a	4615.23ab	28.10a	34.29c

Values reported are the mean for three replications. Mean values of a different letter in the same column are significantly different (p<0.05)

Table 5. Effect of location factor on days to biological, grain and straw yield (kg/ha), harvest index, and 1000 kernel weight (g)

Location	Biological Yield	Grain Yield	Straw yield	Harvest index	1000 Kernel weight
Maru	8473.89a	2465.73a	6008.16a	31.19a	36.44a
Mushager	3963.49c	977.78c	2985.71c	21.93c	--
Rabba	5601.79b	1558.93b	4042.85b	27.42b	33.11b

Table 5 reveals that the Maru site has a significant effect ($p < 0.001$) on biological yield, grain yield, straw yield, harvest index, and 1000 kernel weight compared to the Mushager and Rabba sites. The biological yield at the Maru site was found to be 53% and 33% higher than at Mushager and Rabba, respectively. Furthermore, the grain yield at the Maru location is 60.3% and 36.7% higher than at Mushager and Rabba. On the other hand, the Mushager location had the lowest grain yield and straw yield, as well as longer days to heading and maturity.

3.4. Correlation between experimental locations and wheat yield and traits

Table 6 shows the correlation coefficient at the Maru site, where the DH had a very strong positive correlation with the DM. The DM was also very strongly positively correlated with BY, SY, and 1000KW. The BY was very strongly positively correlated with GY and SY. In contrast, the GY was very strongly correlated with SY. GY has a weak positive correlation with HI. Table 7 illustrates the correlation coefficient at the Mushager site. The correlation varied from strong to very strong for most parameters, except the correlation between DH and SY, and between SY and HI, which was moderate. Table 8 shows the correlation coefficient at the Rabba site. The correlation coefficient between DH and PH, and GY was a negative moderate correlation. The correlation between PH and BY, GY, and SY was a very weak negative correlation. Table 9 shows the correlation coefficient and its significance for the wheat trait across the study area. The correlation coefficient between DH and PH, and GY was a negative moderate correlation. In contrast, the correlation between PH and BY, GY, and SY was a very weak negative correlation.

3.5. Stability for grain yield

The environment-centered GGE biplot showed a positive correlation between Maru, Mushager, and Rabba (an acute angle < 900). The varieties Ammoun and Um Qais are in the same group, Hourani and Mixture are in the same group, while ACSAD 65 and Dair Alla 6 form another group.

Table 6. Maru trait correlation for days to heading, days to maturity, plant height, biological, grain and straw yield, harvest index, and 1000 kernel weight

	DH	DM	PH	BY	GY	SY	HI	1000KW
DH	1							
DM	0.87***	1						
PH	0.53***	0.62***	1					
BY	0.65***	0.83***	0.69***	1				
GY	0.55***	0.76***	0.63***	0.93***	1			
SY	0.66***	0.83***	0.69***	0.99***	0.88***	1		
HI	-0.50***	-0.55***	-0.46***	-0.64***	-0.35***	-0.71***	1	
1000KW	0.73***	0.83***	0.66***	0.78***	0.72***	0.78***	-0.50***	1

Notes: DH = Days of Heading, DM = Days of Maturity, PH = Plant Height, BY = Biomass Yield, GY = Grain Yield, SP= Straw Yield, HI = Harvest Index and 1000KW = 1000 Kernel Weight, *** Significant at p< 0.001

Table 7. Mushager trait correlation for days to heading, days to maturity, plant height, biological, grain and straw yield, harvest index and 1000 kernel weight

	DH	DM	PH	BY	GY	SY	HI
DH	1						
DM	0.91	1					
PH	0.83	0.85	1				
BY	0.63	0.66	0.76	1			
GY	0.73	0.76	0.84	0.94	1		
SY	0.55	0.57	0.69	0.98	0.86	1	
HI	0.73	0.71	0.72	0.65	0.78	0.56	1

Notes: DH = Days of Heading, DM = Days of Maturity, PH = Plant Height, BY = Biomass Yield, GY = Grain Yield, SP= Straw Yield, HI = Harvest Index and 1000KW = 1000 Kernel Weight

Table 8. Rabba trait correlation for days to heading, days to maturity, plant height, biological, grain and straw yield, harvest index, and 1000 kernel weight

	DH	DM	PH	BY	GY	SY	HI	1000KW
DH	1							
DM	0.96***	1						
PH	-0.49***	-0.57***	1					
BY	0.57***	0.62***	-0.20	1				
GY	-0.04	0.07	-0.10	0.58***	1			
SY	0.72***	0.71***	-0.18	0.88***	0.12	1		
HI	-0.36**	-0.26	0.02	0.11	0.85***	-0.37**	1	
1000KW	-0.55***	-0.56***	0.23	-0.13	0.51***	-0.46***	0.67***	1

Notes: DH = Days of Heading, DM = Days of Maturity, PH = Plant Height, BY = Biomass Yield, GY = Grain Yield, SP= Straw Yield, HI = Harvest Index and 1000KW = 1000 Kernel Weight, ** Significant at p<0.01, *** Significant at p< 0.001

Table 9. Correlation coefficient and its significance for the wheat trait across the study area.

	DH	DM	PH	BY	GY	SY	HI	1000KW
DH	1							
DM	0.91***	1						
PH	-0.4***	-0.16*	1					
BY	-0.29***	0.04	0.66***	1				
GY	-0.43***	-0.12	0.67***	0.87***	1			
SY	-0.21**	0.11	0.61***	0.98***	0.76***	1		
HI	-0.34***	-0.27***	0.42***	0.18*	0.56***	0.02	1	
1000KW	-0.22	0.14	0.5	0.56	0.66	0.48	0.21	1

Notes: DH = Days of Heading, DM = Days of Maturity, PH = Plant Height, BY = Biomass Yield, GY = Grain Yield, SP= Straw Yield, HI = Harvest Index and 1000KW = 1000 Kernel Weight,*Significant at p<0.05, ** Significant at p<0.01, *** Significant at p< 0.001

Um Qais performed above average in Maru, Ammoun performed above average in all sites, and Mixture performed below average in all locations (Fig. 5). The mean performance and genotype stability reveal that the entries are ranked along the AEA, with the meeting point of the two perpendicular lines representing the average mean, and ranking is done based on the direction arrow, with the highest being behind the pointed section of the arrow.

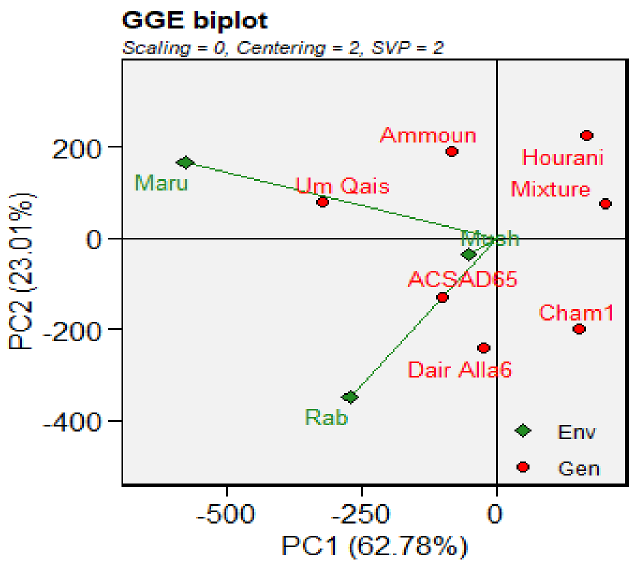


Figure 5. Grain yield environment-centered GGE biplot in the three locations

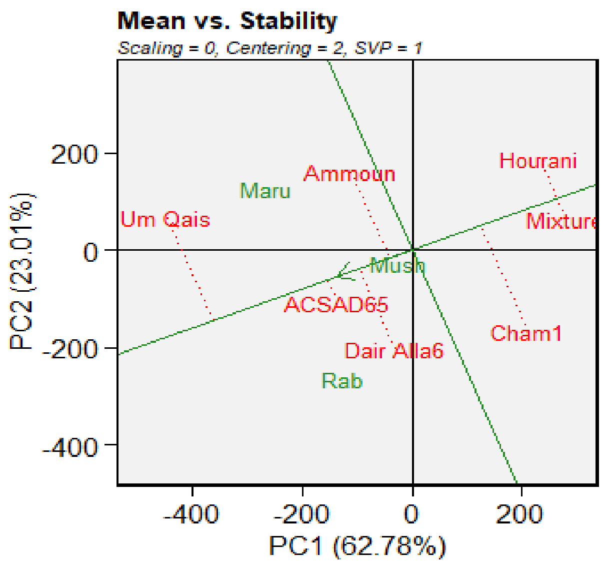


Figure 6. Mean performance and stability of varieties for grain yield in the three locations

The vertical black line distinguishes entries with below-average means from those with above-average means, and the genotype with the shorter projection is the most stable. In contrast, the genotype with lengthy projections is less stable. Figure 6 depicts the mean vs stability across all three locations. The entries in Figure 6 were ranked as follows: Um Qais (with the greatest mean) > ACSAD 65 > Dair Alla6 > Ammoun > Cham1 > Hourani, Mixture. As a result, Um Qais had the highest average wheat grain production among the three locations, whereas Hourani and Mixture had the lowest yield. In this scenario, Um Qais and Cham1 are the least stable, whereas ACSAD 65, Hourani, and Mixture are the most stable. Figure 7 shows the Which-Won-Where Pattern in Multi-Environments. For which-won-where, the perpendicular lines divide the biplot into six sectors. Line 1 was perpendicular to the side that connects varieties Cham1 and Mixture; Line 2 was perpendicular to the extension of Mixture and Hourani; Line 3 was perpendicular to side Hourani and Ammoun; Line 4 was perpendicular to side Ammoun and Um Qais; Line 5 was perpendicular to side Um Qais and Dair Alla6; Line 6 was perpendicular to side of Dair Alla6 and Cham1. Out of the six sectors, the environments fall into two of them. One mega environment was characterized, containing Maru and Mushager. Um, Qais performed better in Maru and Mushager's environment. Also, Dair Alla6 performed better at Rabba (Fig. 7). PC explains 85.79% of total variations.

Figure 8 shows the mean vs stability in Maru and Mushager, Maru the ranking of the entries was as follows: Um Qais (with the highest mean) > Ammoun > ACSAD 65> Dair Alla6 > Hourani> Mixture> Cham1. Therefore, Um Qais had the highest mean for wheat grain yield at Maru, while Cham1 had the lowest yield at Maru. Ammoun was less stable with a longer projection, while Um Qais was the most stable. Um Qais was the best entry at Maru, with the highest yield and more stable. For Mushager, the order of the entries was as follows: Um Qais (with the highest mean) > Hourani > ACSAD 65> Cham1> Dair Alla6 > Mixture> Ammoun. As a result, Um Qais had the greatest average wheat grain yield at Maru, while Ammoun had the lowest. ACSAD 65 and Dair Alla6 were the least stable entries with longer projections, while Hourani, Cham1, and Mixture were the most stable. In contrast, Figure 9 shows the mean vs. stability in Rabba. The ranking of the entries was as follows: Um Qais (with the highest mean) > Dair Alla6 > ACSAD 65> Cham1> Hourani, Ammoun> Mixture. Therefore, Um Qais had the highest mean for wheat grain yield at Rabba, while Mixture had the lowest grain yield at Rabba. Ammoun was less stable with more extended projection, while ACSAD65, Cham1, and Hourani were the most stable entries at Rabba.

4. DISCUSSION

This study provides critical insights into the influence of varieties, environmental conditions, and their interactions on wheat yield and associated traits across three distinct locations in Jordan. The findings emphasize the significance of variety-environment interactions in optimizing wheat production in arid and semi-arid regions, offering valuable implications for sustainable agriculture and food security.

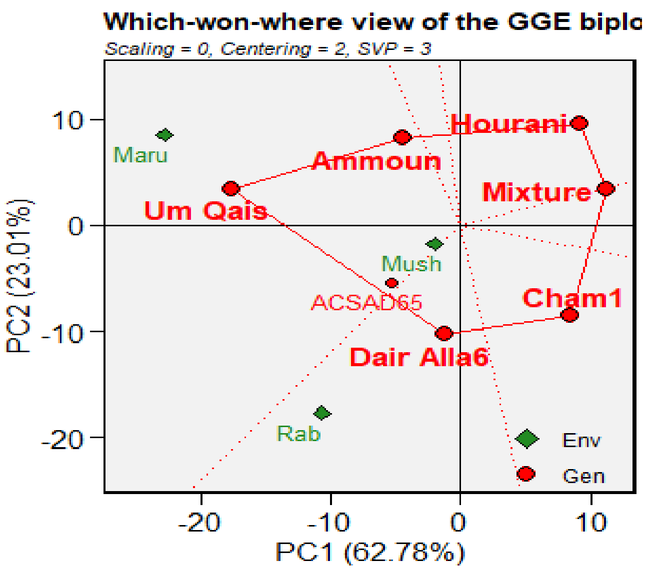
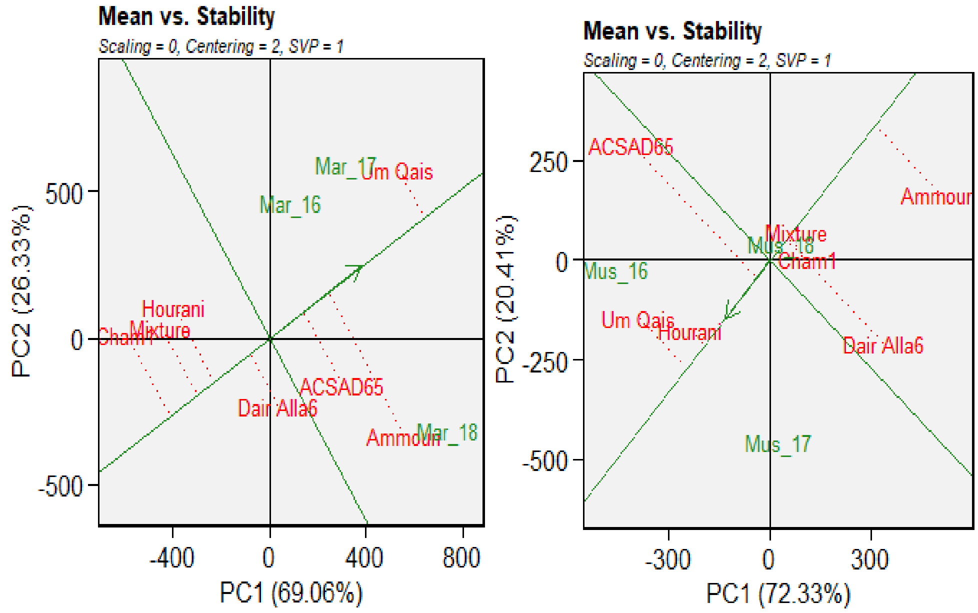


Figure 7. Which-Won-Where Pattern in Multi-Environments



a) Maru b) Mushager

Figure 8. Mean performance and stability of varieties for grain yield in Maru and Mushager

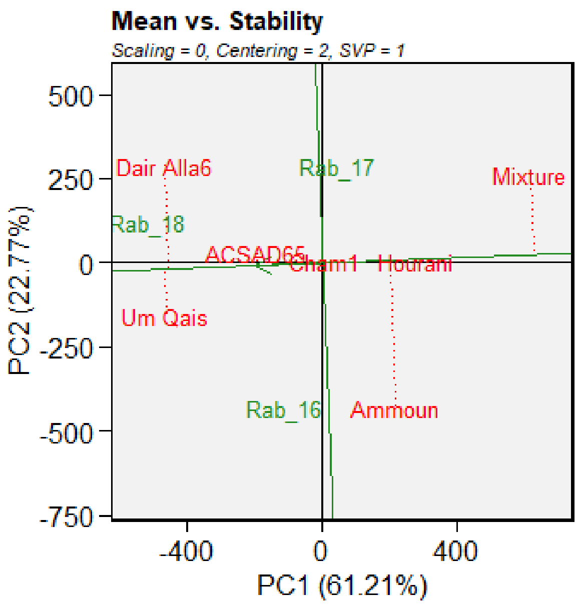


Figure 9. Mean performance and stability of variety for grain yield in Rabba

The study highlights the substantial influence of both varieties and environmental conditions on wheat yield and morphological traits. Among the tested varieties, Um Qais consistently outperformed the others, exhibiting a 20% higher grain yield compared to the mixture genotype, 17.5% higher than Hourani, and 15.2% higher than Cham1 (Table 4). This superior performance can be attributed to its genetic adaptability to variable environmental conditions, as supported by Al-Sayaydeh et al. (2023), who emphasized the role of genotypic adaptability in enhancing crop performance. Moreover, stability analysis confirmed Um Qais as the most stable and high-performing variety, particularly at the Maru site, which exhibited the most favorable environmental conditions. The Maru site exhibited the most favorable environmental conditions for wheat production, characterized by higher annual rainfall (431 mm), clay-rich soil with balanced nutrient availability, and moderate salinity. These factors collectively supported superior plant height, early maturity, and higher grain and biological yields. In contrast, Mushager and Rabbah, with lower rainfall and differing soil properties (clay loam and silty clay, respectively), exhibited reduced plant growth and yield performance, highlighting the critical role of site-specific environmental conditions in genotype performance evaluation. This is consistent with previous studies indicating that variety stability is crucial in determining consistent yield performance under fluctuating climatic conditions (Saeidnia et al., 2023; Yan & Holland, 2010).

Environmental factors, particularly soil fertility and rainfall distribution, played a pivotal role in determining wheat productivity. Maru, with its higher soil fertility and favorable rainfall, demonstrated a 53% and 33% advantage in biological yield over Mushager and Rabba, respectively, and a 60.3% and 36.7% higher grain yield (Table 3). These findings align with the work of Zampieri et al. (2020), who identified rainfall patterns and soil fertility as critical determinants of crop productivity in Mediterranean climates. The significant genotype-by-environment interaction, as revealed by the ANOVA analysis (Table 3), underscores the necessity of selecting varieties suited to specific environmental conditions. The superior performance at Maru can be explained by enhanced nutrient uptake and photosynthetic activity during critical growth phases, driven by the site's favorable environmental conditions.

Morphological traits such as plant height and developmental timing (days to heading and maturity) also exhibited significant variation, reflecting the varieties' adaptation to environmental conditions. Early heading varieties like ACSAD65 completed critical growth stages before the onset of water stress and high temperatures, demonstrating their suitability for water-limited environments. This finding aligns with Sayyah et al. (2012), who highlighted the adaptive advantage of early-heading traits in arid regions. Plant height, which varied significantly among varieties, was positively correlated with biomass yield, particularly at Maru, where taller plants were associated with 28% and 27% greater biomass compared to Mushager and Rabba, respectively (Fig. 4). These results reinforce the role of plant height as an important indicator of productivity potential under optimal conditions, as previously noted by Reynolds et al. (2009).

The findings of this study have significant implications for sustainable wheat production in Jordan. This study identifies Um Qais as a high-yielding and relatively stable wheat variety, particularly under the favorable conditions of the Maru site. Its consistent performance across three growing seasons and locations, as confirmed by GGE biplot analysis and significant varieties-environment interactions, underscores its suitability for targeted deployment in similar agro-ecological zones in Jordan. These findings can inform regional variety selection strategies aiming to improve wheat productivity under site-specific conditions. This approach supports broader food security goals in arid and semi-arid regions, where environmental constraints frequently limit crop production. This study highlights the importance of evaluating wheat varieties in semi-arid agro-ecological zones of Jordan, as exemplified by Maru, Mushager, and Rabbah. These regions, characterized by annual rainfall between 350–430 mm, are typical of semi-arid Mediterranean climates where water scarcity and climatic variability challenge wheat production. Furthermore, these findings underscore the necessity for ongoing investment in breeding programs to develop varieties that better adapt to local environmental conditions. The observed genetic variability among the tested varieties lays the groundwork for enhancing traits such as drought tolerance, early maturity, and high biomass production, which are crucial for mitigating the impacts of climate change on wheat production. Previous studies, such as those by Asseng et al. (2015), predict a 6% global reduction in wheat yield for every 1°C increase in temperature, highlighting the urgency of developing climate-resilient varieties. The integration of advanced breeding techniques, including marker-assisted selection and genomic selection, could facilitate the identification of wheat varieties with improved stress tolerance. Additionally, optimizing agronomic practices such as conservation tillage, crop rotation, and supplemental irrigation may further enhance productivity in water-limited regions (Hatfield & Prueger, 2015). Despite the valuable insights gained, this study has certain limitations. The evaluation was conducted over three growing seasons, which may not fully capture the long-term effects of variety-environment interactions. Additionally, the study focused on a limited number of locations and varieties, potentially limiting the generalizability of the findings to broader environmental and genetic conditions in Jordan. Future research should focus on long-term evaluations of genotype performance under diverse environmental conditions, including simulated climate change scenarios. Integrating advanced technologies such as high-throughput phenotyping, genomic selection, and remote sensing could accelerate the identification of varieties with desirable traits, such as drought resistance and nutrient-use efficiency (Araus & Cairns, 2014). Moreover, exploring the potential of combining improved varieties with sustainable farming practices, such as water harvesting and soil conservation, could enhance wheat production in Jordan and similar regions. Finally, multi-location and multi-year trials, along with economic assessments of the most promising varieties, would provide more comprehensive recommendations for policymakers and farmers.

5. CONCLUSION

This study demonstrates that both genotype and environmental conditions, along with their interactions, play a pivotal role in determining wheat productivity under rainfed conditions in Jordan. Across three agro-ecological zones and multiple growing seasons, significant variations were observed in phenological traits, plant height, and yield components. Um Qais consistently achieved the highest grain yield among the seven tested wheat varieties, outperforming Mixture, Hourani, and Cham1 by 20%, 17.5%, and 15.2%, respectively. It also demonstrated strong yield performance and adaptability across diverse environments, particularly excelling at the Maru site, which provided the most favorable growing conditions. The GGE biplot stability analysis further supported Um Qais as the most suitable candidate for consistent yield across multiple environments, highlighting its potential for recommendation in breeding and agricultural programs to enhance food security. Additionally, Maru emerged as the most productive location, with significantly higher biological and grain yields compared to Mushager and Rabbah, indicating the critical influence of local edaphic and climatic conditions. In light of these findings, we recommend prioritizing the Um Qais variety in wheat production strategies for semi-arid and rainfed regions in Jordan. Furthermore, integrating this variety into breeding programs focused on stability and high yield is essential. Future research should expand on multi-year and multi-location trials and incorporate advanced phenotyping and genomic tools to further refine genotype recommendations for climate resilience.

Data availability

Data will be available on reasonable request from the corresponding author.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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