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Agromorphological comparison of a durum wheat evolutionary population, a landrace, and a mixture of landraces in the northern of Morocco

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Abstract: Durum wheat (*Triticum turgidum ssp. durum Desf.*) production faces challenges under increasing climate change, biodiversity loss, and the growing need for sustainable and resilient cropping systems. Choice of varieties adapted to local conditions may be of crucial importance to secure future productivity in particular in North African smallholder systems. This work aimed to evaluate the growth and the agronomic traits of four entries of durum wheat, including a common Moroccan landrace (CLH), a mixture of three landraces (MLZSH), an evolutionary population (EP), and a modern variety (MVK). The experiment was carried out over two consecutive growing seasons (2021/2022 and 2022/2023) in three different sites in northern Morocco (Jahjouka, Boujedyane, and Sahel). Analysis of variance revealed significant effects of genotype, location, and year on most traits, along with significant genotype × environment interactions, indicating differential responses among genotypes across environments. However, PCA distinguished three entry groups. Landraces and their mixture exhibited superior growth traits, including greater plant height, tillering capacity, and straw biomass. In contrast, EP and MVK, exhibited higher agronomic traits. Interestingly, the EP matched the agronomic performance of the modern variety, all while preserving moderate growth traits. These results highlight the potential of integrating genetically diverse materials, such as landraces and evolutionary populations, into agroecological strategies. This approach can enhance resilience, conserve genetic resources in situ, and support farmer seed autonomy. This study makes a significant contribution to the broader effort to promote sustainable wheat systems under environmental and socioeconomic constraints.

Keywords: Agroecology, wheat, genetic diversity, evolutionary population.

Introduction

Agricultural production is experiencing significant changes due to accelerated shifts in consumer demand, high input costs, and increasing concerns about food security and the environmental impacts of production (Godfray & Garnett 2014). This phenomenon is particularly evident within the context of current biodiversity loss and climate change (Fischer et al. 2017; Jiren et al. 2020). Agroecology advocating for spatial and temporal diversification to support sustainable and resilient production based on natural regulations was proposed as an alternative (Altieri et al. 1999; Abson et al. 2013; Gaudin et al. 2015; Renard & Tilman 2019). A key strategy of this concept is the enhancement of genetic diversity at the field level, which has been demonstrated to facilitate and enhance disease regulation (Mundt 2002; De Vallavieille 2004), resilience to climate variability (Finckh et al. 2000; Ostergard et al. 2009; Altieri & Nicholls 2013), and agro-ecosystem functioning (Cardinale et al. 2011; Cook-Patton et al. 2011). Increased within-field diversity can be achieved through the cultivation of landraces or old varieties, the mixing or crossing of varieties, and the growing of Composite Cross Populations (CPP) or open-pollinated varieties (Goldringer et al. 2017). Intraspecific diversity endows cultivated crops with the capacity to adapt to change and to stabilize production (Tomich et al. 2011; Reiss & Drinkwater 2018). The stabilizing effect is attributed to the complementarity between genotypes exploiting resources from different ecological niches, facilitation, and sampling effects, which serve to increase the probability of having a genotype adapted to the local conditions (Barot et al. 2017).

Durum wheat (*Triticum turgidum ssp. durum Desf.*) is a well-known cereal that is cultivated in the Mediterranean region for the production of a range of traditional products, including bread, couscous, pasta, and semolina. Here, it is cultivated on a large scale, accounting for approximately 60% of the global durum wheat area (Royo et al. 2017), due to its capacity to adapt to different agroclimatic conditions. In Morocco, wheat is grown on 2.8 million hectares under rainfed conditions (FAOSTAT 2023). Winter cereals account for more than 55% of the country's agricultural areas, with common and durum wheat making up around 75% of this total (Bouras et al. 2020). At the same time, this crop is among those facing challenges in the context of climate change, since drought induced yield gaps of durum wheat were projected to increase in the future (Hou et al. 2024).

In an attempt to respond to these challenges, this study aims to investigate the use of intraspecific diversity of durum wheat entries to maintain and enhance the productivity of smallholder agricultural systems in Morocco. We hypothesized that evolutionary populations, landraces, and mixture of landraces may be used in these systems because of their genetic diversity inferring adaptability to local conditions, while reducing dependence of farmers on seed companies.

Indeed, wheat landraces, defined as dynamic populations with the historical origin, distinct identity, and high variability (Villa et al. 2024), have a high tolerance to biotic and abiotic stresses (Dwivedi et al. 2016), high yield stability, and an average yield in low-input environments (Zeven 1998; Balfourier et al. 2007; Xynias et al. 2019; Shlibak et al. 2021). These landraces have been cultivated within low-input farming systems, a process that has resulted in the preservation of traits which serve to enhance their adaptability to conditions that might be deemed suboptimal from an environmental and climatic perspective (Lopes et al. 2015; Frankin et al. 2021). Notable among these traits are increased plant height, which enhances competitiveness against weeds (Spina 2018; Eser 2024), and reduced susceptibility to drought, particularly in landraces selected in semi-arid regions, attributable to the development of a deep root system (Waines & Ehdaie 2007; Lopes et al. 2015; Bektas et al. 2016; Moragues et al. 2006; Nakhforoosh et al. 2021). During the last century, there was a decline in the cultivation of wheat landraces by farmers, who instead opted for high-yielding commercial varieties. The modern improved varieties are superior to landraces in terms of characteristics such as earliness, reduced plant height, and resistance to lodging. The narrow genetic composition of modern cultivars limits their capacity to adapt to changing environmental conditions. Consequently, they exhibit heightened susceptibility to environmental stresses. In contrast, landraces characterized by intraspecific heterogeneity and lower grain yield demonstrated consistent performance across a broad spectrum of environments, resulting in enhanced stress tolerance (Adhikari et al. 2022). However, the ongoing replacement of these landraces with new, improved varieties has contributed to the erosion of biodiversity (Lopes et al. 2015; Shlibak et al. 2021) and increased vulnerability of the crops.

Recently, genetic diversity in wheat crops was introduced by the development of evolutionary populations (EPs) (also referred to as bulk populations or composite crosses), which are obtained by mixing the F1 or the F2 seed obtained by crossing a number of varieties in all or several combinations. EPs demonstrated their ability to adjust their phenology to the environment where they evolve, to become higher yielding, to give a more stable yield, and to have a superior resistance to diseases (Ceccarelli & Grando 2022). Mixtures are obtained by mixing the seed of a number of varieties and can be either static or dynamic (Wolfe & Ceccarelli 2020). Static mixtures are those which are reconstituted from their original component varieties at the beginning of each growing season and therefore do not evolve. Dynamic mixtures are those which are derived from the seed harvested from the preceding cropping season. This process effectively converts dynamic mixtures into evolutionary populations, thus enabling evolution. The utilization of both EPs and mixtures has been demonstrated to increase yield in barley (Solimane Allard 1991; Raggi et al. 2017) and bread wheat (Bocci et al. 2020). Additionally, Brumlop et al. (2017) demonstrated that EPs are comparable with modern cultivar in terms of yield ability under organic conditions.

The objective of this study is to evaluate the performance of evolutionary populations, landraces, and mixtures by studying their growth and agronomic parameters in Moroccan smallholder low-input systems. To this end, we compared the performance of intra-specifically diverse landraces and evolutionary populations and their mixtures at three different locations to a commercial modern variety. We hypothesized that intra-specifically diverse wheat populations would perform better than the commercial high yield modern variety under these conditions.

Materials and Methods

Plant Material

The material used in the trials included four entries of durum wheat, namely an evolutionary population (EP) composed of all lines resulting from crosses between local and modern varieties of durum wheat, a mixture of three landraces, namely Zarriai, Swini and Hmimar (MLZSH), a common landrace Hmimar (CLH) widely cultivated in the region and a common modern durum wheat variety Karim (MVK) that was selected as control based on its popularity among farmers, its potential for high yields, and its commercial value.

Experimental Sites

The selected durum wheat entries were cultivated over two consecutive growing seasons (2021/2022 and 2022/2023) at three different sites: Jahjouka (35°00'44.64"N to 5°43'42.6"O; m 143 a.s.l), Boujedyane (35°06'27.72"N to 5°47'31.55"O; m 85 a.s.l), and Sahel (35°15'25.2"N to 6°06'26.28"O; 149 m a.s.l), all located within the Larache province (Tanger-Tetouan-Al Hoceima region) in Morocco (Figure 1).

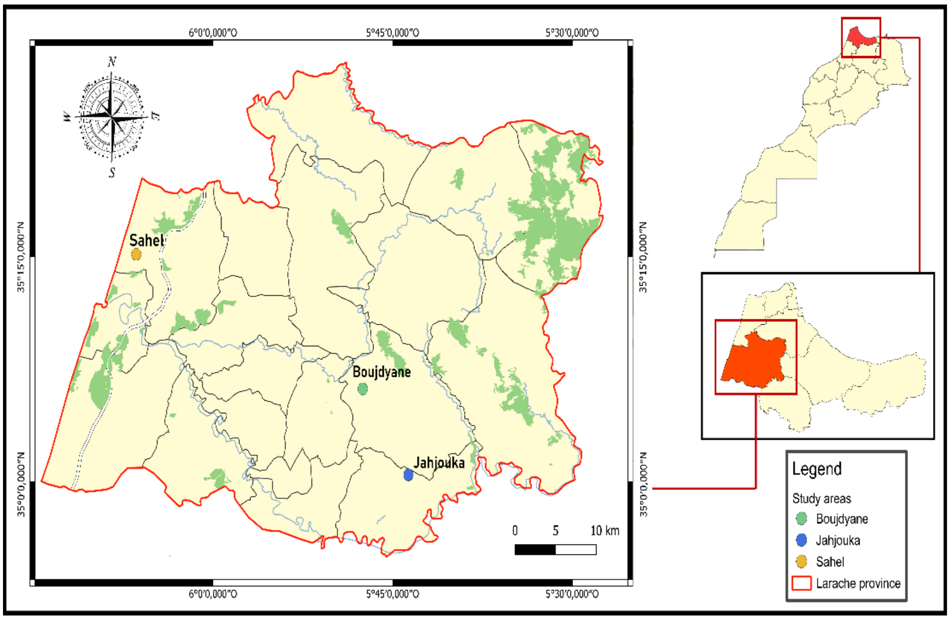


Figure 1. Study sites in the province of Larache (Morocco).

Sites characteristics

The study area is characterized by a typical Mediterranean climate, with cool winters and warm to hot summers. Jahjouka and Boujedyane exhibited similar climatic conditions due to their geographical proximity, with a mean temperature of 16.30°C and total precipitation of 307.28 mm, whereas Sahel showed relatively higher temperatures (17.14°C) and lower precipitation (283.47 mm) in 2021/2022. However, in the second year, both Jahjouka and Boujedyane maintained comparable conditions with a mean temperature of 16.69 °C and total precipitation of 545.31 mm, while Sahel was characterized by higher temperature levels (17.85 °C) and total precipitation of 440.14 mm (Table 1).

Table 1. Annual rainfall (mm), and average of temperature (oC) at Jahjouka, Boujedyane, and Sahel during 2021/2022 and 2022/2023.

Location	Temperature (^{o}C)		Precipitation (mm)	
	2021/2022	2022/2023	2021/2022	2022/2023
Jahjouka	16.30	16.69	307.28	545.31
Boujedyane	16.30	16.69	307.28	545.31
Sahel	17.14	17.85	283.47	440.14

The Jahjouka site is characterized by clayey silt soil with a normal level of organic matter. Among the main elements, calcium (Ca) and magnesium (Mg) show high values, while phosphorus (P) is normal, and potassium (K) has a low concentration. Regarding trace elements, the concentrations of copper (Cu), manganese (Mn), and zinc (Zn) are normal; however, iron (Fe) is high. Additionally, the soil in Jahjouka has normal conductivity and pH, but a high concentration of sodium (Na). Boujedyane shares many traits with Jahjouka, except for its normal iron (Fe) and low zinc (Zn) concentrations. Regarding the Sahel site, the soil that hosted trials was characterized by a sandy-loam texture, poor in organic matter with normal concentrations of the main and trace elements, except for potassium (K), copper (Cu), and zinc (Zn), which are low. The conductivity and pH levels are normal, while the sodium (Na) concentration is high, as it is at the other two sites (Table 2).

Table 2. Soil properties of the experimental sites.

SOIL PHYSICO-CHEMICAL PROPERTIES	JAHJOUKA	BOUJEDYANE	SAHEL
Clay (%)	39.94	39.95	5.00
Silt (%)	39.94	39.95	9.99
Sand (%)	20.12	20.11	85.01
Bulk density (g/cm3)	0.99	1.05	1.27
fine soil density (g/cm3)	0.96	1.04	1.24
Mass water content (g/g)	0.21	0.16	0.06
Mass of gravel (g)	26.22	11.04	36.58
mass of organic matter (g)	0.45	1.12	0.89
pH	5.73	7.67	6.32
Ca (méq/g)	32.22	42.00	8.57
Mg (méq/g)	8.63	5.02	1.25
P (mg/kg)	27.86	73.77	71.91
K(méq/g)	0.12	0.10	0.04
Cu (ppm)	1.51	0.96	0.18
Fe (ppm)	70.77	17.25	75.55
Mn (ppm)	36.46	23.86	1.91
Zn (ppm)	0.79	0.58	0.73
CE (mS/cm)	0.12	0.20	0.12
Na (méq/g)	2.67	2.66	2.11

Experimental design and trial management

In the three sites (Jahjouka, Boujedyane, and Sahel), the entries were sown at the end of December in each growing season (2021/2022 and 2022/2023) by hand at a rate of 14 g/m², and harvested in June when the entire plot reached the harvest maturity stage (Zadoks scale: GS 92). At all sites, chickpea and white bean were grown as pre-crops in both years of the study. The tested entries were cultivated under rainfed conditions without any supplementary irrigation and according to the routine farm practices.

At each site, the entries were blocked according to the previous crop, within which three plots (1 m^2) were selected from the central area to minimize border effects. These plots were considered as an experimental unit, resulting in six replicates per entry per location.

Within each plot, five plants were randomly sampled for the measurement of growth and agronomic traits.

Data collection

Growth parameters

Seven growth parameters were measured: number of tillers per plant (NTP), number of fertile tillers per plant (NFTP), number of nodes (NN), straw height (SH in cm), plant height (PH in cm), spike length (SL in cm), and distance between the last leaf and the spike (LLSD in cm).

Agronomic parameters

The agronomic parameters studied were: number of sterile spikelets per spike (NSSP), spike weight (SW in g), number of grains per spike (NGS), spike yield (SY in g), thousand kernel weight (TKW in g), and grain yield (GY in g/m²).

All the traits were measured on individual plants sampled randomly (15 plants per plot), except for the thousand-kernel weight and grain yield, which were measured at the plot level.

Statistical analysis

Growth and agronomic parameters of four entries cultivated in three sites, during two growing seasons, were subjected to three-way analysis of variance (ANOVA) to estimate the effect of entries, locations, years, and their interactions using R (4.5.3). Trait values were calculated as plot-level means. Prior to analysis, ANOVA assumptions were assessed. Normality of residuals was evaluated using the Shapiro–Wilk test, and homogeneity of variances was tested using Levene’s test. Mean comparisons were performed using Tukey’s (HSD) test at a 5% significance level. To investigate the relationship between each pair of variables, correlation coefficients were estimated based on Pearson’s correlation method. Principal Component Analysis (PCA) was used to examine relationships among traits and entries. All variables were standardized prior to analysis to ensure comparability among traits measured in different units.

Results

Analysis of variance

Effect of entries, locations, years, and their interaction on growth parameters

Analysis of variance values for all the traits, including the significance of entry (E), location (L), year (Y), and interactions effects are shown in Table 3. The three main effects (E, L, and Y) showed significant P-values for all the traits, except for NN, which showed no significant effect of year. For the two-way interactions (L × Y, L × E, and Y × E), significant effects were detected for most traits except for NN, it was significant only in the case of location× entry interaction, while LLSD was not significant. However, the location × year interaction was not significant for NN and SL. The three-way interaction (G × L × Y) was significant only for SH, PH, SL, and LLSD.

Effect of entries, locations, years, and their interaction on agronomic parameters

The ANOVA results for the recorded growth traits are summarized in Table 4. Significant differences due the main effect of Location, Year, and Entry were observed for the most of the parameters except for SY. In terms of doubles interactions, Site x Year interaction was significant only for GY and TKW. While, Year x Entry interaction was significant for all the studied parameters. Year x Entry interaction was also significant except for SY, GY. Moreover, the triple interaction was significant for all the parameters except of SY and TKW.

Table 3. ANOVA for growth parameters of an evolutionary populations, landrace, mixture of landraces and a modern variety during two years (2021/2022-2022/2023) in three locations in Morocco.

Source of variation	Df	NTP		NFTP		NN		SH		PH		SL		LLSD	
		F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)
Location	2	10.84	4.71E-05 ***	31.40	1.08E-11 ***	26.44	3.07E-10 ***	182.02	4.55E-37 ***	158.04	2.38E-34 ***	5.68	4.38 E-03 **	138.33	7.00E-32 ***
Year	1	196.53	4.88E-27 ***	122.40	4.84E-20 ***	0.00	0.95 ns	171.03	7.75E-25 ***	139.84	7.27E-22 ***	11.76	8.29 E-04 ***	683.35	2.25E-51 ***
Entry	3	17.22	2.31E-09 ***	8.98	2.05E-05 ***	123.58	1.53E-36 ***	299.91	1.44E-55 ***	292.86	5.07E-55 ***	55.21	1.70E-22 ***	40.42	3.96E-18 ***
Location x Year	2	17.54	2.07E-07 ***	33.87	2.18E-12 ***	0.58	0.56 ns	27.72	1.27E-10 ***	23.45	2.54E-09 ***	1.08	0.34 ns	36.55	4.00E-13 ***
Location X Entry	6	4.08	9.24E-04 ***	3.52	3E-03 **	7.18	1.46E-06 ***	15.98	1.93E-13 ***	15.09	8.24E-13 ***	5.77	2.65E-05 ***	1.69	0.13 ns
Year x Entry	3	13.72	9.45E-08 ***	6.03	7.39E-04 ***	2.32	0.08 ns	24.16	2.67E-12 ***	22.59	1.16E-11 ***	15.05	2.24E-08 ***	87.31	4.94E-30 ***
Location x Year x Entry	6	2.28	4.09E-02 *	2.06	0.06 ns	1.67	0.132 ns	7.67	5.51E-07 ***	7.27	1.22E-06 ***	4.26	6.28 E-04 ***	19.24	1.28E-15 ***

Table 3. ANOVA for agronomic parameters of an evolutionary populations, landrace, mixture of landraces and a modern variety during two years (2021/2022-2022/2023) in three locations in Morocco.

Source of variation	Df	NSSP		SW		NGS		SY		GY		TKW	
		F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)
Location	2	25.73	5.02E-10 ***	120.30	2.14E-29 ***	55.77	7.48E-18 ***	16.26	5.63E-07 ***	193.86	2.59E-38 ***	217.69	1.19E-40 ***
Year	1	27.30	7.45E-07 ***	23.12	4.45E-06 ***	5.56	1.99 E-02 *	0.53	0.47 ns	30.75	1.77E-07 ***	16.20	1 E-04 ***
Entry	3	121.18	3.70E-36 ***	41.11	2.40E-18 ***	99.68	1.94E-32 ***	5.19	2.10 E-03 **	26.10	4.55E-13 ***	27.46	1.37E-13 ***
Location x Year	2	0.38	0.68 ns	1.15	0.32 ns	2.24	0.11 ns	0.79	0.46 ns	20.78	1.78E-08 ***	61.34	4.46E-19 ***
Location X Entry	6	2.49	0.03 *	5.79	2.53E-05 ***	11.21	6.54E-10 ***	1.34	0.24 ns	6.54	5.41E-06 ***	2.55	2.34 E-03 *
Year x Entry	3	16.88	3.28E-09 ***	15.36	1.61E-08 ***	12.48	3.69E-07 ***	0.76	0.52 ns	1.45	0.23 ns	2.95	3.55 E-02 *
Location x Year x Entry	6	5.17	9.34E-05 ***	5.03	1.25 E-04 ***	6.15	1.21E-05 ***	0.82	0.55 ns	4.10	8.92 E-04 ***	1.26	0.28 ns

Means of growth parameters

Variation across locations

Significant differences among locations were observed for most of the studied traits. Boujedyane showed the highest values for NTP (2.17), NFTP (2.08), and NN (4.63), and was significantly different from Jahjouka and Sahel. It also recorded the highest SH (88 cm), PH (95,91 cm), and LLSD (37,71 cm), although this value was not significantly different from Jahjouka. In contrast, Sahel exhibited the lowest values for most traits, including NTP (1.68), NFTP (1.32), SH (66.47 cm), PH (74.43 cm), and LLSD (28.67 cm), and was significantly different from the other locations except for NFTP. Jahjouka showed intermediate values, particularly for NTP (1.94) and NFTP (1.64). However, no significant differences among locations were observed for SL, indicating a similar spike length across locations (Table 5).

Table 4. Means ± standard deviations of seven growth parameters measured in tree locations for two years.

Location	NTP	NFTP	NN	SH	PH	SL	LLSD
Jahjouka	1.94 ±1.05 ^{ab}	1.64±0.82 ^{b}	4.23±0.65 ^{b}	80.06±20.25 ^{a}	87.55±20.81 ^{a}	7.49±1.59 ^{a}	36.07±12.54 ^{a}
Boujedyane	2.17±1.21 ^{a}	2.08±1.16 ^{a}	4.63±0.85 ^{a}	88±20.03 ^{a}	95.91±20.92 ^{a}	7.91±1.51 ^{a}	37.71±8.25 ^{a}
Sahel	1.68±1.10 ^{b}	1.32±0.66 ^{b}	4.32±0.62 ^{b}	66.47±15.46 ^{b}	74.43±16.57 ^{b}	7.95±1.85 ^{a}	28.67±7.63 ^{b}

NTP=number of tillers per plant, NFTP=number of fertile tillers per plant, NN=number of nodes, SH=straw height in cm, PH=plant height in cm, SL=spike length in cm, LLSD=distance between the last leaf and the spike in cm. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Entries variability

CLH and MLZSH exhibited comparable levels of significance for several growth traits, including the number of tillers per plant (NTP), number of nodes (NN), straw height (SH), plant height (PH), spike length (SL) and distance between the last leaf and spike (LLSD), with CLH recorded the highest NTP (2.25), the longest straw (SH) (91,8 cm), and the longest plant (PH) (36,28 cm), being significantly taller than the other entries. Similarly, the longest distance between the last leaf and the spike (LLSD) was recorded in CLH (36,28 cm). While, MLZSH was showed the highest NN (4,91) and the longest spike length (8,71 cm). However, EP showed an intermediate performance in terms of NTP (1,86), SH (70,76 cm), PH (78,13 cm), SL (7,37 cm), and LLSD (34,6 cm). Interestingly, the modern variety (MVK) exhibited the lowest value of all growth parameters except for the number of nodes (NN). MVK was the shortest in terms of straw height (58.93 cm), plant height (65.66 cm), spike length (6.72 cm), and distance between the last leaf and spike (LLSD) (29.78 cm). In addition, this entry showed the lowest number of tillers and fertile tillers per plant, respectively (1.45; 1.36) (Table 6).

Table 5. Means ± standard deviation of seven growth parameters measured in an evolutionary population (EP), a common landrace (CLH), a mixture of landraces (MLZSH), and a modern variety (MVK).

ENTRIES	NTP	NFTP	NN	SH	PH	SL	LLSD
CLH	2.25±1.31^{a}	1.90±1.15 ^{a}	4.77±0.68 ^{a}	91.8±20.14 ^{a}	100.13±20.28 ^{a}	8.33±1.32 ^{a}	36.28±13.79 ^{a}
MLZSH	2.17±1.21^{a}	1.78±0.95 ^{b}	4.91±0.71 ^{a}	91.22±18.5 ^{a}	99.92±18.53 ^{a}	8.71±1.6 ^{a}	35.95±12.6 ^{a}
EP	1.86±1,04^{ab}	1.68±0.90 ^{b}	4±0.48 ^{b}	70.76±9.19 ^{b}	78.13±9.,93 ^{b}	7.37±1.83 ^{b}	34.60± 5.59^{ab}
MVK	1.45±0.74^{b}	1.36±0.7 ^{c}	3.9±0.39 ^{b}	58.93±10.11 ^{c}	65.66±10.78 ^{c}	6.72±1.6 ^{c}	29.78±12.6 ^{b}

NTP=Number of tillers per plant, NFTP=number of fertile tillers per plant, NN=number of nodes, SH=straw height in cm, PH=plant height in cm, SL=spike length in cm, LLSD=distance between the last leaf and the spike in cm. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Inter-annual variation

All the studies entries had higher SH (84.27 cm), PH (91.84 cm) and LLSD (40.33 cm) in 2021/2022 compared to 2022/2023. On the other hand, NTP (2.54), NFTP (2.11) and SL (7.99 cm) were lower in 2021/2022 compared to the growing season of 2022/2023, while no significant differences were found for NN.

Table 6. Means ± standard deviation of seven growth parameters measured on four wheat entries during 2021/2022 and 2022/2023.

YEARS	NTP	NFTP	NN	SH	PH	SL	LLSD
2022	1.32±0.57 ^{b}	1.25±0,51^{b}	4.4±0.73 ^{a}	84.27±21.6 ^{a}	91.84±22.39 ^{a}	7.57±1.55 ^{b}	40.33±9.83 ^{a}
2023	2.54±1.23 ^{a}	2.11±1.1 ^{a}	4.39±0.74 ^{a}	72.09±17.79 ^{b}	80.08± 18.66 ^{b}	7.99±1.76 ^{a}	27.97±6.83 ^{b}

NTP=Number of tillers per plant, NFTP=number of fertile tillers per plant, NN=number of nodes, SH=straw height in cm, PH=plant height in cm, SL=spike length in cm, LLSD=distance between the last leaf and the spike in cm. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Means of agronomic traits

Variation across locations

Boujedyane was the site that had significantly the highest SW (2.55 g), NGS (40.48), SY (2g), GY (225.72 g/m2), and TKW (43.96 g), while Sahel had the lowest values. Sahel and Jahjouka were the locations with the highest value of NSSP (2.53 and 2.32 respectively) and intermediate value of SW (1.81g), NGS (32,67), GY (116.24g/m^2), and TKW (37.78g).

Table 7. Means ± standard deviation of six agronomic parameters measured in three locations.

LOCATION	NSSP	SW	NGS	SY	GY	TKW
Jahjouka	2.32±2.01 ^{a}	1.81±0.71 ^{b}	32.67±13.21 ^{b}	1.21±0.57 ^{b}	116.24±80.68 ^{b}	37.78±4.61 ^{b}
Boujedyane	1.49±1.56 ^{b}	2.55±0.82 ^{a}	40.48±14.83 ^{a}	2±3.43 ^{a}	225.72±88.44 ^{a}	43.96±4.52 ^{a}
Sahel	2.53±1.93 ^{a}	1.43±0.68 ^{c}	28.67±11.43 ^{b}	0.98±0.51 ^{b}	36.49±36.84 ^{c}	29.12±7.35 ^{c}

NSSP=number of sterile spikelets per spike, SW=spike weight in g, NGS=number of grains per spike, SY=spike yield in g, GY=grain yield in g/m2), TKW=thousand kernel weight in g. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Entries variability

Significant differences among entries were observed for most of the studied traits. EP and MVK showed the highest values for yield-related traits, particularly NGS (39.02 and 44.17, respectively) and SY (1.69g and 1.58g), and were significantly superior to CLH and MLZSH. Concurrently, EP recorded the highest grain yield (167.43 g/m^2), and SW (2,31), followed by MVK. Also in terms of TKW, EP showed the highest average (40,88g), significantly exceeding all other entries. However, CLH and MLZSH exhibited higher values for NSSP (3.54 and 3.05, respectively), an intermediate value of TKW (36.34g;37.2g) and lower performance for yield components such as SW (1.45g;1,81g), NGS (24.03;28,52), GY (94,46 g/m^2;91,0146 g/m^2) and SY(0,9g;1,41g).

Table 8. Means ± standard deviation of six agronomic parameters measured in evolutionary population (EP), common landrace (CLH), mixture of landraces (MLZSH), and a modern variety (MVK).

ENTRIES	NSSP	SW	NGS	SY	GY	TKW
CLH	3.544±1.57 ^{a}	1.456±0.58 ^{c}	24.039±6.86 ^{b}	0.904±0.37 ^{b}	94.468±69.76 ^{bc}	36.34±7.17^{ab}
MLZSH	3.05±1.62 ^{a}	1.81±0.85 ^{bc}	28.52±8.81 ^{b}	1.41±3.97 ^{ab}	91.01±64.56^{c}	37.2±6.63^{ab}
EP	0.97±1.21 ^{b}	2.31±0.79 ^{a}	39.02±11.62 ^{a}	1.69±0.63 ^{a}	167.43±137.5 ^{a}	40.88±8.85 ^{a}
MVK	0.89±1.46 ^{b}	2.16±0.95 ^{ab}	44.17±16.69 ^{a}	1.58±0.75 ^{a}	154.68±111.95 ^{ab}	33.51±8.76 ^{b}

NSSP=number of sterile spikelets per spike, SW=spike weight in g, NGS=number of grains per spike, SY=spike yield in g, GY=grain yield in g/m2), TKW=thousand kernel weight in g. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Inter-annual variation

The highest values for SW (2.08g) and GY (148.5 g/m^2) were recorded in the first cropping season (2022/2023), while NSSP (2.44) and NGS (35.03) reached their maximum in the second year of the experiment. while no significant differences were found for spike yield (SY), number of grains per spike (NGS), and thousand kernel weight (TKW).

Table 9. Means ± standard deviation differences of phenotypic parameters during 2021/2022 and 2022/2023.

Years	NSSP	SW	NGS	SY	GY	TKW
2022	1.78±1.48 ^{b}	2.08±0.88 ^{a}	32.84±12.1 ^{a}	1.34±0.66 ^{a}	148.5±89.18 ^{a}	38.15±4.81 ^{a}
2023	2.44±2.19 ^{a}	1.79±0.84 ^{b}	35.03±15.77 ^{a}	1.45±2.85 ^{a}	105.29±116.03 ^{b}	35.82±10.56 ^{a}

NSSP=number of sterile spikelets per spike, SW=spike weight in g, NGS number of grains per spike, SY=spike yield in g, GY=grain yield in g/m2), TKW=thousand kernel weight in g. Different letters indicate significant differences according to Tukey's HSD test ($p < 0.05$).

Heatmaps

Growth parameters

Number of tillers per plant

In Boujedyane, in the first year of the experiment, the number of tillers per plant (NTP) was not significant, with EP having the highest number. In contrast, during the second year, CLH had the highest number of tillers, while MVK had the lowest. In Jahjouka, CLH and MLZSH had the highest number of tillers in both growing seasons. In contrast, the modern variety (MVK) showed the lowest tiller number. In the case of Sahel, no significant difference was found between entries during the 2021/2022 growing season as all had 1 tiller. In the second year, MLZSH had the highest number of tillers. As expected, the modern variety showed the lowest value.3.4.1.2 Number of fertile tillers per plant

Concurrently, a similar trend was observed for the number of fertile tillers, except in the Sahel site, where EP had the highest value during the 2022/2023 growing season. As expected, the modern variety (MVK) always showed the lowest number of fertile tillers.

Number of nodes

In Boujedyane and Sahel sites, MLZSH and EP showed the highest and the lowest number of nodes in 2021/2022, respectively. In 2022/2023, the highest number of nodes was observed in CLH and the lowest value in MVK. Regarding Jahjouka, the highest number of nodes was found in MLZSH and the lowest in MVK in both growing seasons.

Straw height

In Boujedyane, the maximum straw height was observed in MLZSH during 2022, while CLH reached the highest value in 2023. In Jahjouka, CLH consistently recorded the tallest straw across both cropping seasons. In Sahel, CLH showed the greatest straw height in 2022, but EP surpassed all other entries in 2023. On the contrary, MVK consistently demonstrated the lowest straw height across all locations and seasons.

Plant height

The same pattern was observed for plant height. In Boujedyane, MLZSH showed the tallest plants in the 2021/2022 season, while CLH was the tallest in 2022/2023. In Jahjouka, CLH was the tallest entry during both growing seasons. Similarly, in Sahel, CLH had the tallest plants in 2021/2022, but in 2022/2023, EP became the tallest. Overall, the modern variety (MVK) consistently exhibited the shortest plants.

Spike length

The longest spike was assigned for MLZSH in Boujedyane during the study period. As well as, in Jahjouka in 2022/2023. However, in Jahjouka, the longest spike was recorded for CLH in the first year of the experiment. Regarding the Sahel, MLZSH was always the entry with the longest spike in 2021/2022, while, in the second year, the evolutionary population (EP) registered the longest spike. In contrast, the shortest spike was displayed by EP in 2021/2022 and MVK in 2022/2023, respectively in all three locations.

Distance between the last leaf and spike

In Boujedyane, CLH and EP recorded the longest distance between the last leaf and the spike in 2022, while, MVK displayed the shortest distance. A similar pattern was observed for EP in 2023, whereas MLZSH showed the shortest distance. In Jahjouka, the longest distance in 2022 was recorded in CLH, and the shortest in MVK. However, in 2023, the trend was reversed, with CLH recording the shortest distance, and EP showing the longest. In the Sahel, CLH had the longest distance in 2022, and EP recorded the longest in 2023. MVK consistently displayed the shortest distance in both cropping seasons.

Agronomic parameters

Number of sterile spikelets per spike

In Boujedyane, the highest number of sterile spikelets per spike was found in CLH during the first growing season (2021/2022), while in the following season, MLZSH showed the highest number of sterile spikelets. In contrast, MVK consistently had the lowest number of sterile spikelets in both growing seasons. In Jahjouka in 2021/2022, MLZSH had the highest number of sterile spikelets per spike while EP had the lowest. During the 2022/2023 cropping season, CLH had the highest NSSP, while MVK had the lowest number. In Sahel, CLH had the highest NSSP in both cropping seasons, whereas the lowest NSSP was recorded in MVK and EP.

Spike weight

In Boujedyane, during the first cropping season (2021/2022), the heaviest spike was observed in MVK, while the lightest spike was recorded in CLH. In the second year (2022/2023), the EP produced the heaviest spikes, while MLZSH and CLH had the lightest ones. In Jahjouka, both EP and MVK had the heaviest spikes, while CLH consistently had the lightest spike in both cropping seasons; a similar trend was observed in 2022/2023. In the Sahel, in the first cropping season MVK had the heaviest spike, while CLH had the lightest. However, in the second year, this trend was reversed, with MVK producing the lightest spike and EP recording the heaviest.

Number of grains per spike

In Boujedyane, MVK recorded the highest number of grains per spike (NGS) in both cropping seasons. In contrast, the lowest NGS was observed in CLH and MLZSH in 2021/2022 and 2022/2023, respectively. In Jahjouka, MVK consistently exhibited the highest NGS, while CLH recorded the lowest in both cropping seasons. In the Sahel, the highest NGS was recorded in MVK in the 2022 season and in EP in 2023 season. In contrast, CLH showed the lowest NGS in both years.

Spike yield

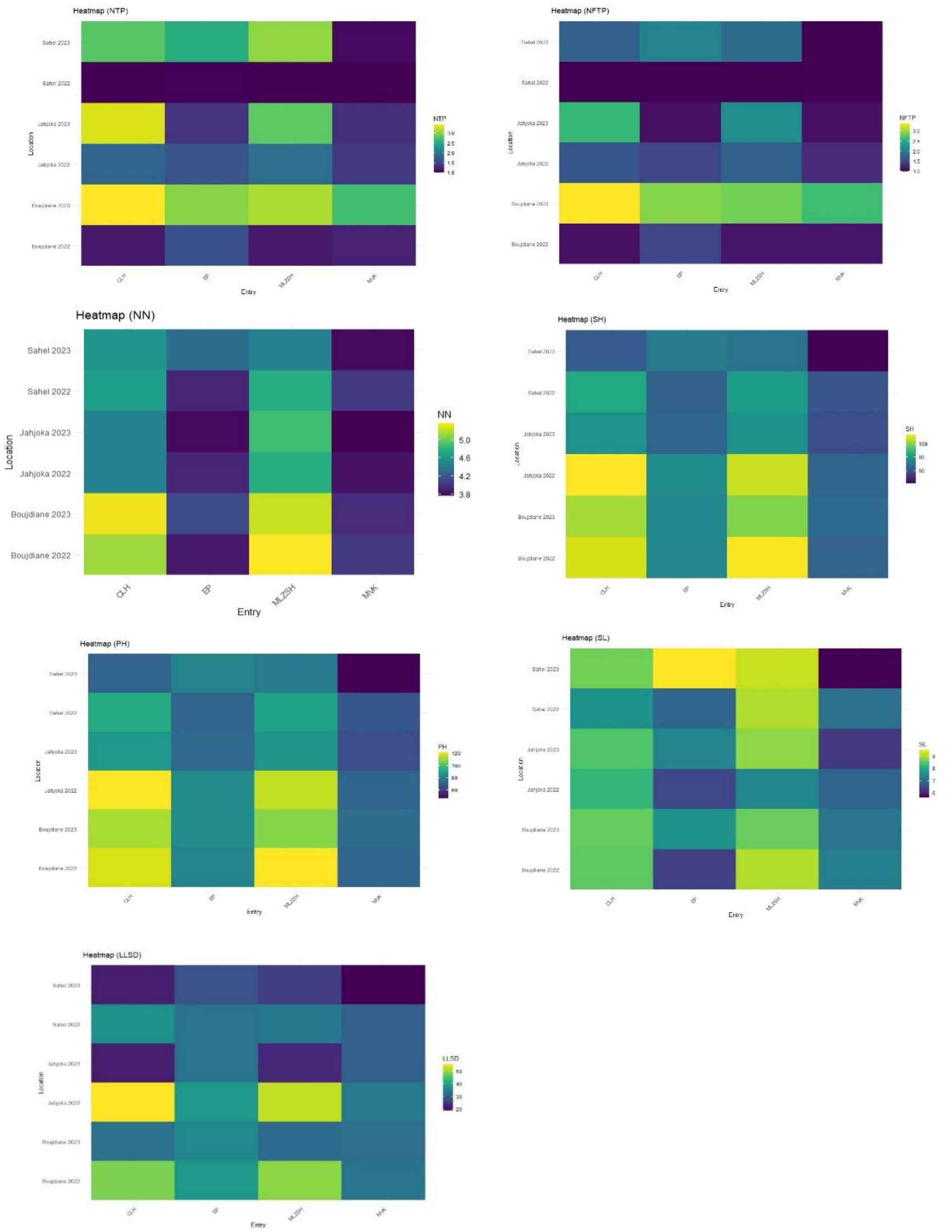
In Boujedyane, the highest spike yield was recorded in MVK in 2022 season and in MLZSH during 2023. In Jahjouka, EP achieved the highest spike yield in 2022, while in the second year, the highest spike yield was recorded in MVK. In the Sahel, EP consistently produced the highest spike yield in both growing seasons. Overall, CLH presented the lowest spike yield in the three locations during the two growing seasons, except in the Sahel in 2023, MVK showed the lowest average.

Thousand kernel weight

In Boujedyane, the highest value of TKW was observed in the EP while the lowest value was recorded in MVK in both growing seasons. In Jahjouka, the highest value of thousand kernel weight was observed in the EP in both cropping seasons. However, the lowest one was recorded in CLH in 2022 and in MLZSH and MVK in 2023. In the Sahel, EP had the highest value of TKW. However, MVK registered the lowest value in both the two years of the experiment.

Grain yield

In Boujedyane, MVK gave the highest yield in 2022, while the lowest one was CLH. In 2023, the highest yielding entry was the EP while the lowest yielding was MLZSH. In Jahjouka, EP was the best performing entry in 2022, while MLZSH was the lowest yielding entry. In 2023, MVK was the highest yielding entry, while CLH was the lowest yielding entry. In Sahel, MVK gave the highest yield in 2022 and MLZSH showed the lowest grain yield. The trend was reversed in 2023.



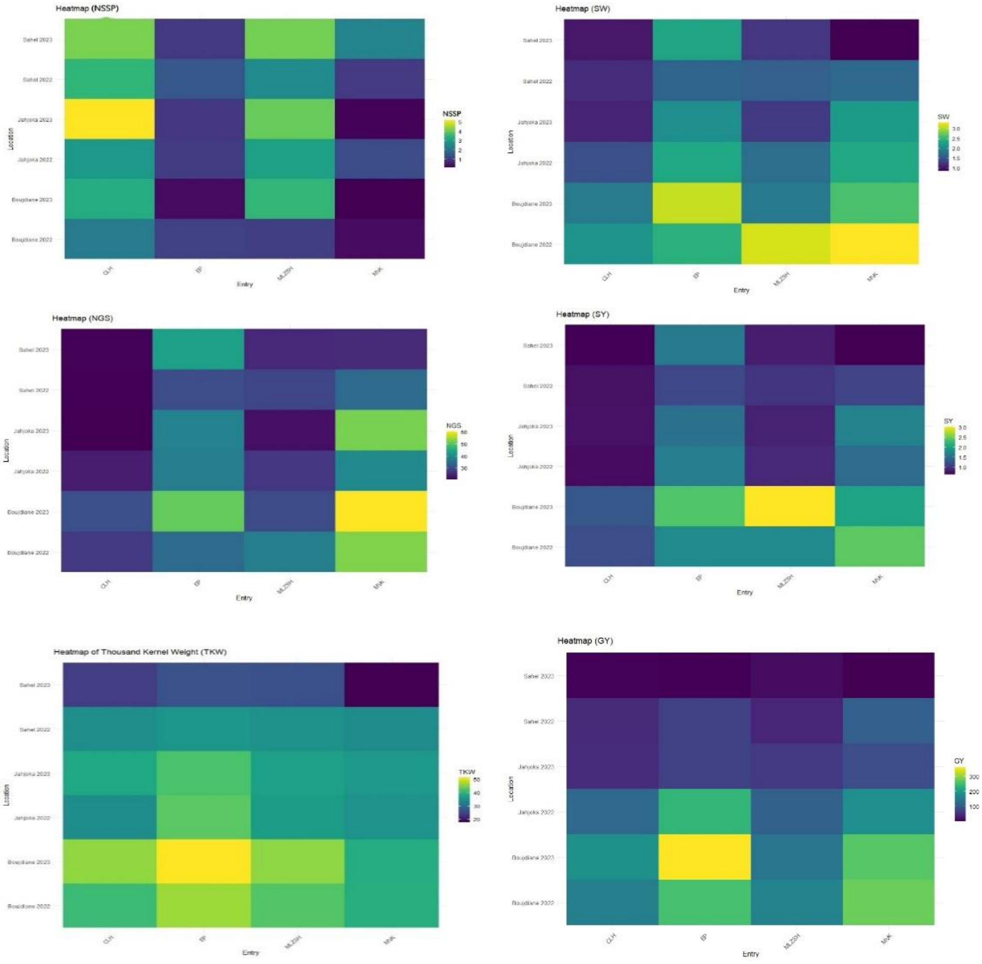


Figure 2. Heatmaps of growth parameters of four durum wheat entries (Evolutionary population (EP), Common landrace (CLH), Mixture of landraces (MLZSH), and a modern variety (MVK)), across three locations (Jahjouka, Boujedyane, and Sahel) during two growing seasons (2021/2022 and 2022/2023).

Correlation between parameters

The correlation matrix analysis between the 13 studied parameters showed that there is a significant correlation between phenotypic and agronomic parameters, within agronomic traits, and finally within phenotypic parameters (Figure 4).

Correlation between agronomic parameters

A strong high positive correlation was observed between SW, TKW (r = 0.87), SY (r = 0.96), NGS (r = 0.88), as well as between GY and TKW (r = 0.82). A positive correlation was found between SY, TKW (r = 0.82), and NGS (r = 0.79). In addition, the NGS was also correlated with TKW (r = 0.62). SW was positively correlated with GY (r = 0.62). However, NSSP exhibited a negative correlation with all agronomic parameters. Interestingly, GY revealed non-significant correlations with SY (r= 0.54) and NGS (r = 0.29).

Correlation between growth parameters

The correlation coefficients between the phenotypic parameters are shown in Figure 4. NFTP exerted a strong, significant positive association with NTP (r = 0.9), LLSD (r = 0.84).

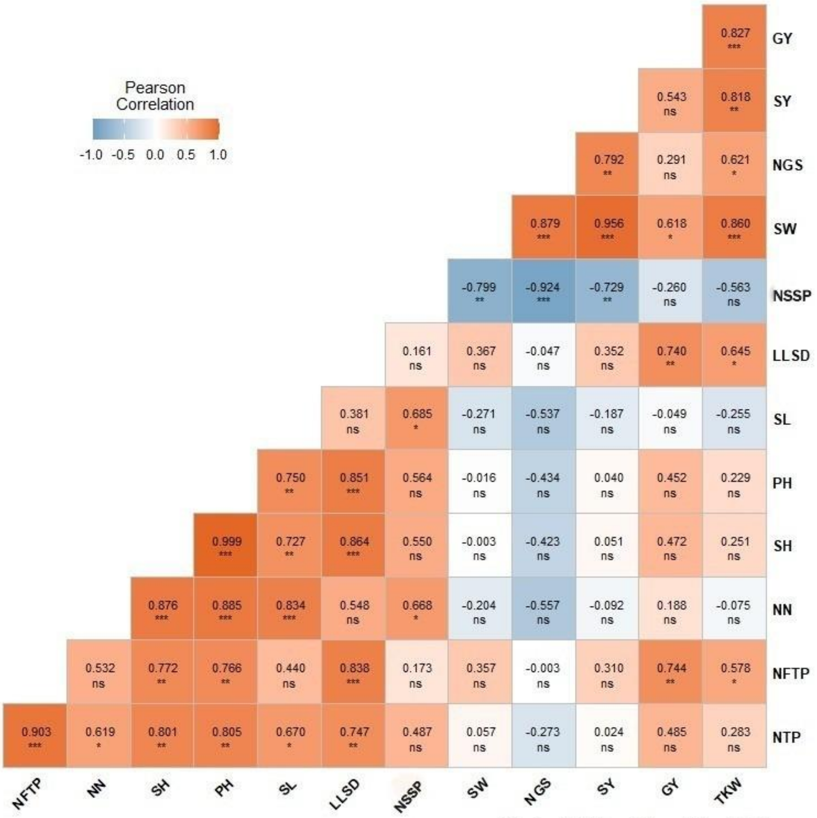
Concurrently, LLSD was strongly and positively correlated with PH (r = 0.86), SH (r = 0.86). Likewise, NN was strongly and positively correlated with SL (r = 0.83), PH (r = 0.89) and SH (r = 0.88). In addition, a positive correlation was found between NTP and LLSD (r = 0.75), PH (r = 0.8), and SH (r = 0.8). Similarly, NFTP was positively correlated with PH (r = 0.77), SH (r = 0.77). Furthermore, SL had a highly significant and positive correlation with SH (r = 0.72) and PH (r = 0.76).

Correlation between growth and agronomic parameters

The analysis showed a positive correlation between grain yield (GY), number of fertile tillers per plant (NFTP) (r = 0.74), and LLSD (r = 0.74). Furthermore, a positive correlation was observed between (TKW), NFTP (r = 0.58), and LLSD (r = 0.65). Similarly, NSSP had a positive correlation with NN (r = 0.67), SL (r = 0.69), whereas a highly significant and negative correlation was observed between the number of grains per spike (NGS) and the phenotypic parameters. As well as between NSSP and SY (r= -0.73), SW (r = -0.8). No significant correlation was detected in terms of SW and SY with other phenotypic parameters.

Principal component analysis

A principal component analysis (PCA) of 13 phenotypic and agronomic traits of the four durum wheat entries (CLH, MLZSH, EP and MVK) in the three locations (Jahjouka, Boujedyane, and Sahel) showed that most of the information is correlated with the first two factorial axes (Table 8), which together contain 87.19% of the total variance. The first factorial axis F1 was distinguished, accounting for 48.27% of the variance. It was highly correlated with the growth parameters: SH (0.98), PH (0.98), NTP (0.89), NFTP (0.85), NN (0.85) and LLSD (0.85). However, the second factorial axis F2, which explained 38.92% of the total variance, was mainly associated with the agronomic parameters: SW (0.97), TKW (0.93), SY (0.91), NGS (0.85) and GY (0.71), while it was negatively correlated with NSSP (-0.8). The projection of the entries on the factorial plane (1, 2) made it possible to divide the entries into three groups according to their correlation with the parameters studied. The first group consisted of the two entries MLZSH and CLH in the Jahjouka (JMLZSH and JCLH) and Boujedyane (BMLZSH and BCLH) sites, showed a positive correlation with PC1 and had similar phenotypic traits, characterized by a high number of tillers (NTP) and fertile tillers (NFTP) as well as high number of nodes (NN), height plant (PH), long spike (SL), long straw (SH) and with a significant distance between the last leaf and spike (LLSD). However, the MVK and EP entries from Jahjouka (JEP and JMVK) and Boujedyane (BEP and BMVK) clustered into a separate group, positively correlated with PC2. This group was characterized by high grain yield (GY), spike yield (SY), thousand kernel weight (TKW), spike weight (SW), and number of grains per spike (NGS), coupled with a low number of sterile spikelets per spike (NSSP). Finally, the four studied entries from the Sahel site formed another distinct group, negatively correlated with both PC1 and PC2. This group was characterized by low values for all studied parameters, except for MLZSH and CLH, which displayed moderate value of the growth parameters.



ns p >= 0.05; * p < 0.05; ** p < 0.01; and *** p < 0.001

Figure 3. Pairwise correlation (Pearson's coefficients) using growth and agronomic data (Number of tillers per plant (NTP), number of fertile tillers per plant (NFTP), number of nodes (NN), straw height (SH, cm), plant height (PH, cm), spike length (SL, cm) distance between the last leaf and spike (LLSD, cm), number of sterile spikelets per spike (NSSP), spike weight (SW, g), number of grains per spike (NGS), spike yield (SY, g), grain yield (GY, g/m), thousand kernel weight (TKW, g), of four entries of durum wheat grown across three locations during two growing seasons.

Table 10. Table of coordinates.

	DIM.1	DIM.2	DIM.3	DIM.4	DIM.5	DIM.6	DIM.7	DIM.8	DIM.9	DIM. 10	DIM.11
NTP	0.89	0.06	-0.12	0.42	-0.04	0.04	0.04	0.04	-0.03	-0.04	0.00
NFTP	0.85	0.39	-0.17	0.27	0.08	0.08	-0.09	-0.10	0.01	0.02	0.00
NN	0.85	-0.28	0.31	-0.21	0.18	0.10	-0.08	0.03	0.03	-0.05	0.00
SH	0.98	-0.02	0.05	-0.16	-0.07	-0.01	-0.06	-0.01	0.00	0.03	0.00
PH	0.98	-0.03	0.07	-0.15	-0.07	-0.02	-0.05	-0.01	0.00	0.03	0.00
SL	0.75	-0.40	0.45	0.19	0.03	-0.15	0.10	0.00	0.05	0.02	0.00
LLSD	0.85	0.41	-0.15	-0.15	-0.23	-0.09	-0.02	0.01	-0.03	-0.04	0.00
NSSP	0.56	-0.80	-0.10	0.02	-0.03	0.10	0.05	0.12	-0.02	0.03	0.00
SW	0.01	0.97	0.22	0.04	0.01	-0.03	-0.02	0.03	-0.01	-0.04	0.00
NGS	-0.41	0.85	0.20	0.17	-0.04	-0.01	-0.16	0.10	0.02	0.04	0.00
SY	0.04	0.91	0.36	-0.08	0.00	0.10	0.12	-0.03	-0.08	0.02	0.00
GY	0.51	0.71	-0.35	-0.11	0.28	-0.11	0.04	0.05	-0.02	0.01	0.00

TKW	0.27	0.93	-0.15	-0.09	-0.08	0.09	0.11	0.02	0.11	0.00	0.00

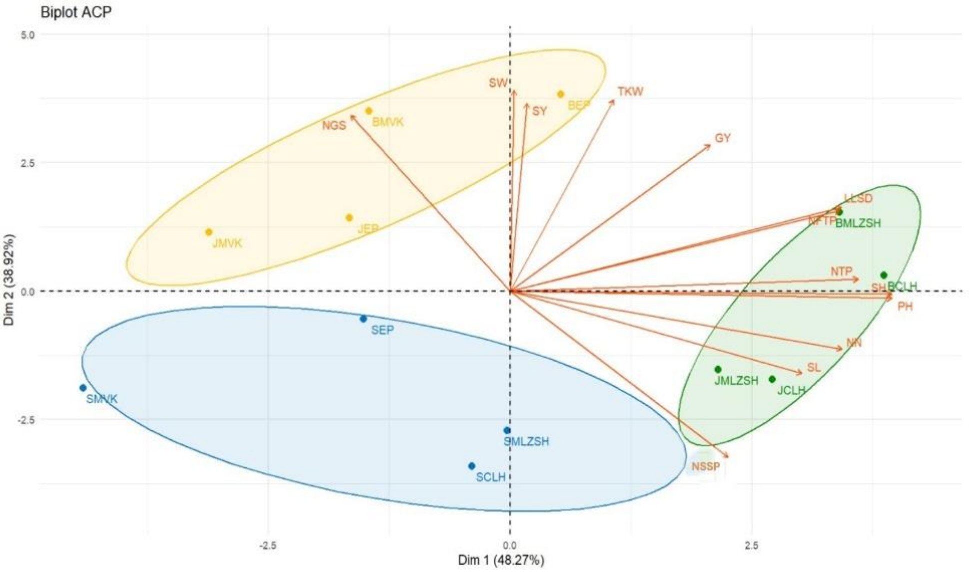


Figure 5. Biplot of principal component analysis. Variables are shown as vectors (Number of tillers per plant (NTP), number of fertile tillers per plant (NFTP), number of nodes (NN), straw height (SH, cm), plant height (PH, cm), spike length (SL, cm), distance between the last leaf and spike (LLSD, cm), number of sterile spikelets per spike (NSSP), spike weight (SW, g), number of grains per spike (NGS), spike yield (SY, g), grain yield (GY, g/m), thousand kernel weight (TKW, g).

Discussion

To address our hypothesis that evolutionary populations, landraces, and mixture may contribute inferring adaptability to local conditions and enhance productivity of smallholder agricultural systems in Morocco, this study evaluated their agromorphological performance in comparison with a modern durum wheat variety across contrasting environments. The objective was to provide a preliminary assessment of their performance under variable environmental conditions.

The results revealed significant effects of genotype, location, and year for most of the studied traits, highlighting the combined influence of genetic and environmental factors on wheat performance. However, no significant year effect was observed for NN and SY, suggesting a relatively stable expression of these traits across years. Similar trends have been reported in studies on evolutionary populations, landraces, and mixtures of durum wheat have shown that plant height is strongly influenced by genotype, location, and year, whereas grain yield is mainly affected by environmental factors such as location and year, with limited genotypic effect. Similarly, studies on barley evolutionary populations, in comparison with landraces and modern varieties, reported that grain yield, spike length, and thousand kernel weight were not significantly affected by location, while plant height showed a strong environmental response.

In addition, the significant genotype × environment interactions, particularly the genotype × location × year interaction observed for grain yield and plant height, indicate that genotype performance varied across environments and years. This reflects differences in climatic conditions and site-specific factors among the studied environments. The significant interaction between genotypes and environments suggests that genotypes reacted differently to environmental changes (Eltaher et al. 2021). Nevertheless, such interactions make the selection of superior genotypes more challenging, as grain yield may vary depending on the environment (Mohammadi et al. 2015)

This variability can be explained by the combined effect of genetic control and environmental influence on plant development. Quantitative trait loci (QTL) mapping analyses have shown that plant height is strongly associated with the elongation of specific internodes, which are under genetic control (Yu et al .2020). However, the expression of these traits is also influenced by environmental conditions, as the duration and progression of growth stages in wheat vary depending on the environment. In this context, differences in stem elongation and final plant height observed in the present study may be attributed to variations in environmental conditions across locations and years.

The resulting biplot from the PCA clearly shows a clustering of CLH and MLZSH in the same PCA group is explained by their strong vegetative growth, and a low value of agronomic parameters comparing to MVK and EP. This suggests a trade-off between vegetative and reproductive growth, where increased allocation of resources to leaves, stems, and roots may limit the resources available for grain production (Golan et al. 2024). Such allocation patterns can also intensify inter-plant competition for light, water, and nutrients, potentially reducing overall crop productivity. This phenomenon is consistent with the concept of the “tragedy of the commons”, in which traits that enhance individual plant competitiveness may ultimately lead to lower yield at the population level (Hardin, 1968; Rankin et al., 2007). However, the analysis of variance revealed that MLZSH outperformed CLH in terms of SW, NGS and TKW. Conversely, CLH exhibited slightly higher productivity than MLZSH, although the difference was minimal (94.46 g/m² vs. 91.01 g/m²). This result is consistent with the findings of Turner et al. (2020), Li et al. (2023) and Stefan et al. (2024), who showed that increasing the number of varieties does not always increase productivity, and Hoang et al. (2021) and Alsabbagh et al. (2022) even found that increasing genetic diversity generally had a negative effect on yield.

On the other hand, our results suggest that CLH exhibits greater height and lower productivity in comparison to MVK. Indeed, several studies have evaluated the agro morphological characteristics of the two varieties. For instance, in Morocco, Chentoufi et al. (2014) and Chegdali et al. (2022a) reported that the modern variety Karim exhibits a shorter plant compared to some Moroccan landraces. Similarly, Chegdali et al. (2022b) reported that the modern varieties are characterized by a high TKW compared to the Moroccan landraces. The observed morphological variability among these accessions can be attributed to farmers' management of local varieties. In Morocco, farmers grow and produce their own seed in environments where various crop varieties coexist. This practice fosters gene flow between the entries, thus contributing to the spread of genetic diversity. This phenomenon has been reported by Zarkati et al. (2010), Nsarellah et al. (2011), Chentoufi et al. (2014), and Sahri et al. (2014). Other studies have been carried out in Spain (Sanchez-Garcia et al. 2015), Turkey (Gurcan et al. 2017), Italy (Preiti et al. 2022), Greece (Mylonas et al. 2023), Croatia (Spanic et al. 2023) and Canada (Carkner and Entz, 2024). These studies have found that modern varieties have higher productivity, while landraces exhibit greater plant height. A similar pattern was reported by Gharib et al. (2020), who observed that Egyptian landraces surpassed modern cultivars in both plant height and spike length. This morphological advantage is particularly noteworthy, as greater plant height is directly associated with higher straw biomass yield, a trait of considerable agronomic and economic value. Indeed, wheat straw represents one of the most abundant lignocellulosic by products of cereal agriculture (Saha et al., 2005; Talebnia et al., 2010), and its valorization constitutes a significant added value for landrace and mixture of landarces. At the smallholder level, straw is widely used as a fodder resource for livestock, particularly in low-input systems where alternative feed sources are scarce. At a broader scale, bioenergy production through combustion, gasification, and biogas generation (Giuntoli et al., 2013; Kaparaju et al., 2010; Karlsson et al., 2016). From a soil management perspective, straw incorporation enhances microbial activity, regulates soil temperature and moisture, limits erosion, and increases organic matter content (Kumar & Goh, 1999). More recently, Furthermore, wheat straw fibers have been explored as a sustainable alternative for the production of environmentally friendly building materials. As an eco-friendly alternative to wood, wheat straw residues can be used to produce panels (Abobakr et al, 2024). Taken together, these applications suggest that the higher straw biomass potential of landraces and mixtures should be recognized as a valuable agronomic trait, complementing grain yield in the comprehensive evaluation of varietal performance.

Along with increased yields, another consequence of the “Green Revolution” was the incorporation of the dwarfing/height-reducing genes, namely: Rht1 (Rht-B1b), Rht2 (Rht-D1b), Rht-D1c, and Rht8 (Zheng et al. 2011; Green et al. 2012; Lopes et al. 2012; Joudi et al. 2014; Zhang et al., 2016; Chairi et al. 2018). These genes have been shown to reduce coleoptile and internode length, and plant height (Rebetzke et al. 2011; Rebetzke et al. 2012a; Rebetzke et al. 2012b). This, in turn, leads to increased grain yield (Grover et al. 2018) by increasing assimilate partitioning to the spike.

Moreover, the PCA analysis revealed that EP and MVK were grouped, indicating that EP exhibited similar agronomic performance to MVK in terms of NSSP, SW, and SY. However, EPs had moderate values for growth parameters, positioning them between landraces and modern varieties in terms of growth traits. Of particular note, EP outperformed MVK in terms of TKW and GY, suggesting its capacity to evolve and attain commercially relevant yield levels. These findings are consistent with those reported by Ceccarelli and Grando (2020, 2022), Bocci et al. (2020), showing the comparable ability of EPs with modern cultivars in yielding under organic conditions and sometimes even becoming more productive than control entries. Analogous trends have been observed in barley evolutionary populations (Salimi et al.2023).

Conclusion

The present study provided a preliminary agro-morphological assessment of four durum wheat entries comprising a Moroccan landrace (CLH), a mixture of landraces (MLZSH), an evolutionary population (EP), and a modern variety (MVK), in three locations in northern of Morocco. The results indicated significant effects of genotype, location, and year, as well as strong genotype × environment interactions, indicating that wheat performance is highly dependent on environmental variability. Also a significant variation in terms of growth and agronomic traits was observed; Landrace and the mixture of landraces displayed superior growth traits, including greater plant height, higher tillering capacity, and greater straw production, reflecting their historical adaptation to low-input systems and serving as a key resource supporting livestock feeding and soil conservation. However, these advantages were accompanied by low agronomic performances. In contrast, modern variety and evolutionary population demonstrated improved yield components. Interestingly, the EP showed comparable agronomic performance to the modern variety while maintaining moderate growth traits.

These findings reinforce the importance of genetically diverse entries especially landraces and evolutionary populations, in agroecological contexts. Such diversity can contribute to the maintenance of on-farm genetic diversity, which may enhance the adaptive capacity of cropping systems under variable climatic conditions and biotic stresses. Furthermore, as these materials can be multiplied and selected directly by farmers, they offer opportunities to support local seed management practices and reduce reliance on external inputs. Such diversity-based approaches are consistent with agroecological principles, as they promote biodiversity and may improve resource-use efficiency and system flexibility.

While the present results provide valuable insights into the performance of the studied entries under the considered agroecological conditions, further multi-year evaluations are needed to confirm their consistency across a wider range of environments. Building on these results, subsequent research will concentrate on the analysis of yield stability and genotype-by-Environment-by-Year (GGE) interactions. This analysis will employ GGE Biplot and AMMI models to identify the most stable and high-performing entries across seasons and agro-climatic conditions.

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References

Abobakr, H., Raji, M., Essabir, H., Bensalah, M. O., Bouhfid, R., & Qaiss, A. E. K. (2024). Enhancing oriented strand board performance using wheat straw for eco-friendly construction. *Construction and Building Materials, 411*, Articolo 135135. https://doi.org/10.1016/j.conbuildmat.2024.135135

Abson, D. J., Fraser, E. D., & Benton, T. G. (2013). Landscape diversity and the resilience of agricultural returns: A portfolio analysis of land-use patterns and economic returns from lowland agriculture. *Agriculture & Food Security, 2*, Articolo 2. https://doi.org/10.1186/2048-7010-2-2

Adhikari, S., Kumari, J., Jacob, S. R., Prasad, P., Gangwar, O. P., Lata, C., Thakur, R., Singh, A. K., Bansal, R., Kumar, S., Bhardwaj, S., & Subodh Kumar, S. (2022). Landraces potential treasure for sustainable wheat improvement. *Genetic Resources and Crop Evolution*, *69*, 499–523. https://doi.org/10.1007/s10722-021-01310-5

Alsabbagh, P., Gay, L., Colombo, M., Montazeaud, G., Ardisson, M., Rocher, A., Allard, V., & David, J. (2022). Diversity matters in wheat mixtures: a genomic survey of the impact of genetic diversity on the performance of 12 ways durum wheat mixtures grown in two contrasted and controlled environments. *PLoS ONE, 17*(12), Articolo e0276223. https://doi.org/10.1371/journal.pone.0276223

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment, 74*, 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6

Altieri, M. A., & Nicholls, C. I. (2013). The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change, 140*, 33–45. https://doi.org/10.1007/s10584-013-0909-y

Balfourier, F., Roussel, V., Strelchenko, P., Exbrayat-Vinson, F., Sourdille, P., Boutet, G., Koenig, J., Ravel, C., Mitrofanova, O., Beckert, M., & Charm, G. (2007). A worldwide bread wheat core collection arrayed in a 384-well plate. *Theoretical and Applied Genetics, 114,* 1265–1275. https://doi.org/10.1007/s00122-007-0517-1

Barot, S., Allard, V., Cantarel, A., Enjalbert, J., Gauffreteau, A., Goldringer, I., Lata, J.-C., Le Roux, X., Niboyet, A., & Porcher, E. (2017). Designing mixtures of varieties for multifunctional agriculture with the help of ecology. A review. *Agronomy for Sustainable Development, 37,* Articolo 13. https://doi.org/10.1007/s13593-017-0418-x

Bektas, H., Hohn, C. E., & Waines, J. G. (2016). Root and shoot traits of bread wheat (*Triticum aestivum* L.) landraces and cultivars. *Euphytica, 212,* 297–311. https://doi.org/10.1007/s10681-016-1770-7

Bocci, R., Bussi, B., Petitti, M., Franciolini, R., Altavilla, V., Galluzzi, G., Di Luzio, P., Migliorini, P., Spagnolo, S., Floriddia, R., Rosi, G., Petacciato, M., Battezzato, V., Albino, A., Faggio, G., Arcostanzo, C., & Ceccarelli, S. (2020). Yield, yield stability and farmers' preferences of evolutionary populations of bread wheat: a dynamic solution to climate change. *European Journal of Agronomy, 121,* Articolo 126156. https://doi.org/10.1016/j.eja.2020.126156

Bouras, E. H., Jarlan, L., Er-Raki, S., Albergel, C., Richard, B., Balaghi, R., & Khabba, S. (2020). Linkages between rainfed cereal production and agricultural drought through remote sensing indices and a land data assimilation system: a case study in Morocco. *Remote Sensing, 12,* Articolo 4018. https://doi.org/10.3390/rs12244018

Brumlop, S., Pfeiffer, T., & Finckh, M. R. (2017). Evolutionary effects on morphology and agronomic performance of three winter wheat composite cross populations maintained for six years under organic and conventional conditions. *Organic Farming, 3,* 34–50. https://doi.org/10.12924/of2017.03010034

Cardinale, B. J., Matulich, K. L., Hooper, D. U., Byrnes, JE., Duffy, E., Gamfeldt, L., Balvanera, P., O'Connor, M. I., & Gonzalez, A. (2011). The functional role of producer diversity in ecosystems. *American Journal of Botany, 98,* 572–592. https://doi.org/10.3732/ajb.1000364

Carkner, M. K., & Entz, M. H. (2025). Canadian organic wheat breeding with on-farm selection: a case study using landrace and modern parents. *Canadian Journal of Plant Science, 105,* 1–13. https://doi.org/10.1139/cjps-2024-0131

Ceccarelli, S., & Grando, S. (2020). Evolutionary plant breeding as a response to the complexity of climate change. *iScience, 23,* Articolo 101815. https://doi.org/10.1016/j.isci.2020.101815

Ceccarelli, S., & Grando, S. (2022). *Evolutionary plant breeding with an introduction to participatory plant breeding*. Milano: Mimesis Edizioni Srl. Recuperato da https://archive.org/details/evolutionary-plant-breeding

Chairi, F., Vergara-Diaz, O., Vatter, T., Aparicio, N., Nieto-Taladriz, M. T., Kefauver, S. C., Bort, J., Serret, M., & Araus, J. (2018). Post-green revolution genetic advance in durum wheat: the case of Spain. *Field Crops Research, 228,* 158–169. https://doi.org/10.1016/j.fcr.2018.09.003

De Vallavieille-Pope, C. (2004). Management of disease resistance diversity of cultivars of a species in single fields: controlling epidemics. *Comptes Rendus Biologies, 327,* 611–620. https://doi.org/10.1016/j.crvi.2003.11.014

Dwivedi, S. L., Ceccarelli, S., Blair, M. W., Upadhyaya, H. D., Are, A. K., & Ortiz, R. (2016). Landrace germplasm for improving yield and abiotic stress adaptation. *Trends in Plant Science, 21,* 31–42. https://doi.org/10.1016/j.tplants.2015.10.012

Eltaher, S., Baenziger, P. S., Belamkar, V., Emara, H. A., Nower, A. A., Salem, K. F., Alqudah, M. A., & Sallam, A. (2021). GWAS revealed effect of genotype ×

environment interactions for grain yield of Nebraska winter wheat. *BMC Genomics, 22*, Articolo 2. https://doi.org/10.1186/s12864-020-07308-0

Eser, C., Soylu, S., & Ozkan, H. (2024). Drought responses of traditional and modern wheats in different phenological stages. *Field Crops Research, 305*, Articolo 109201. https://doi.org/10.1016/j.fcr.2023.109201

FAOSTAT. (2025). *United Nations Food and Agricultural Organisation*. Recuperato da https://www.fao.org/faostat/en/#compare

Finckh, M., Gacek, E., Goyeau, H., Lannou, C., Merz, U., Mundt, C., Munk, L., Nadziak, J., Newton, A., De Vallavieille-Pope, C., et al. (2000). Cereal variety and species mixtures in practice, with emphasis on disease resistance. *Agronomie, 20*, 813–837. https://doi.org/10.1051/agro:2000177

Fischer, J., Abson, D. J., Bergsten, A., Collier, N. F., Dorresteijn, I., Hanspach, J., Hylander, K., Schultner, J., & Senbeta, F. (2017). Reframing the food-biodiversity challenge. *Trends in Ecology & Evolution, 32*, 335–345. https://doi.org/10.1016/j.tree.2017.02.009

Frankin, S., Roychowdhury, R., Nashef, K., Abbo, S., Bonfil, D. J., & Ben-David, R. (2021). In-field comparative study of landraces vs. modern wheat genotypes under a Mediterranean climate. *Plants, 10*, Articolo 2612. https://doi.org/10.3390/plants10122612

Gaudin, A. C. M., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE, 10*, Articolo e0113261. https://doi.org/10.1371/journal.pone.0113261

Gharib, M. A. A. H., Qabil, N., Salem, H. A., Ali, M. M. A., Awaad, H. A., & Mansour, E. (2020). Characterization of wheat landraces and commercial cultivars based on morpho-phenological and agronomic traits. *Cereal Research Communications, 48*, 450–460. https://doi.org/10.1007/s42976-020-00077-2

Giuntoli, J., Boulamanti, A. K., Corrado, S., Motegh, M., Agostini, A., & Baxter, D. (2013). Environmental impacts of future bioenergy pathways: The case of electricity from wheat straw bales and pellets. *GCB Bioenergy, 5*, 497–512. https://doi.org/10.1111/gcbb.12012

Godfray, H. C. J., & Garnett, T. (2014). Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*, Articolo 20120273. https://doi.org/10.1098/rstb.2012.0273

Golan, G., Weiner, J., Zhao, Y., & Schnurbusch, T. (2024). Agroecological genetics of biomass allocation in wheat uncovers genotype interactions with canopy shade and plant size. *New Phytologist, 242*, 107-120. https://doi.org/10.1111/nph.19576

Goldringer, I., Serpolay, E., Rey, F., & Costanzo, A. (2017). *Varieties and populations for on-farm participatory plant breeding* (DIVERSIFOOD Innovation Factsheet 2). Recuperato da http://www.diversifood.eu/wp-content/uploads/2017/03/diversifood_factsheet2_final.pdf

Green, A. J., Berger, G., Griffey, C. A., Pitman, R., Thomason, W., & Balota, M. (2012). Genetic yield improvement in soft red winter wheat in the Eastern United States from 1919 to 2009. *Crop Science, 52*, 2097–2108. https://doi.org/10.2135/cropsci2012.01.0026

Grover, G., Sharma, A., Gill, H. S., Srivastava, P., & Bains, N. S. (2018). Rht8 gene as an alternate dwarfing gene in elite Indian spring wheat cultivars. *PLoS ONE, 13*, Articolo e0199330. https://doi.org/10.1371/journal.pone.0199330

Gurcan, K., Demirel, F., Tekin, M., Demirel, S., & Akar, T. (2017). Molecular and agro-morphological characterization of ancient wheat landraces of Turkey. *BMC Plant Biology, 17,* 9–18. https://doi.org/10.1186/s12870-017-1133-0

Hoang, T. N., Kopecky, M., & Konvalina, P. (2021). Winter wheat mixtures influence grain rheological and mixolab quality. *Journal of Applied Life Sciences and Environment, 54*(4), 417–428. https://doi.org/10.46909/journalalse-2021-036

Hou, M., Li, Y., Biswas, A., Chen, X., Xie, L., Liu, D., Li, L., Feng, H., Wu, S., Satoh, Y., Pulatov, A., & Siddique, K. (2024). Concurrent drought threatens wheat and maize production and will widen crop yield gaps in the future. *Agricultural Systems, 220,* Articolo 104056. https://doi.org/10.1016/j.agsy.2024.104056

Jiren, T. S., Hanspach, J., Schultner, J., Fischer, J., Bergsten, A., Senbeta, F., Hylander, K., & Dorresteijn, I. (2020). Reconciling food security and biodiversity conservation: participatory scenario planning in southwestern Ethiopia. *Ecology and Society, 25,* Articolo 24. https://doi.org/10.5751/ES-11681-250324

Joudi, M., Ahmadi, A., & Mohammadi, V. (2014). Genetic changes in agronomic and phenologic traits of Iranian wheat cultivars grown in different environmental conditions. *Euphytica, 196*, 237–249. https://doi.org/10.1007/s10681-013-1027-7

Kaparaju, P., Serrano, M., & Angelidaki, I. (2010). Optimization of biogas production from wheat straw stillage in UASB reactor. *Applied Energy, 87,* 3779–3783. https://doi.org/10.1016/j.apenergy.2010.06.005

Karlsson, H., Ahlgren, S., Sandgren, M., Passoth, V., Wallberg, O., & Hansson, P. A. (2016). A systems analysis of biodiesel production from wheat straw using oleaginous yeast: Process design, mass and energy balances. *Biotechnology for Biofuels, 9,* Articolo 229. https://doi.org/10.1186/s13068-016-0640-9

Korpetis, E., Ninou, E., Mylonas, I., Ouzounidou, G., Xynias, I. N., & Mavromatis, A. G. (2023). Bread wheat landraces adaptability to low-input agriculture. *Plants, 12,* Articolo 2561. https://doi.org/10.3390/plants12132561

Kumar, K., & Goh, K. M. (1999). Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. *Advances in Agronomy, 68*, 197–319. https://doi.org/10.1016/S0065-2113(08)60846-9

Li, L., Giller, P., Peng, P., Guo, Y., Zhang, S., Hu, Z., Wang, X., & Zhao, G. (2023). The genetic diversity-productivity effect in wheat cultivar mixtures at multiple levels. *European Journal of Agronomy, 142,* Articolo 126676. https://doi.org/10.1016/j.eja.2022.126676

Lopes, M. S., El-Basyoni, I., Baenziger, P. S., Singh, S., Royo, C., Ozbek, K., Aktas, H., Ozer, E., Ozdemir, F., & Manickavelu, A. (2015). Exploiting genetic diversity from landraces in wheat breeding for adaptation to climate change. *Journal of Experimental Botany, 66*, 3477–3486. https://doi.org/10.1093/jxb/erv122

Mohammadi, R., Farshadfar, F., & Amri, A. (2015). Interpreting genotype × environment interactions for grain yield of rainfed durum wheat in Iran. *The Crop Journal, 3*, 526–535. https://doi.org/10.1016/j.cj.2015.05.003

Moragues, M., del Moral, L. F. G., Moralejo, M., & Royo, C. (2006). Yield formation strategies of durum wheat landraces with distinct pattern of dispersal within the Mediterranean Basin: II. Biomass production and allocation. *Field Crops Research, 95*, 182–193. https://doi.org/10.1016/j.fcr.2005.02.009

Mundt, C. C. (2002). Use of multiline cultivars and cultivar mixtures for disease management. *Annual Review of Phytopathology, 40,* 381–410. https://doi.org/10.1146/annurev.phyto.40.011402.113723

Nakhforoosh, A., Nagel, KA., Fiorani, F., & Bodner, G. (2021). Deep soil exploration vs. topsoil exploitation: distinctive rooting strategies between wheat landraces and wild relatives. *Plant and Soil, 459*, 397–421. https://doi.org/10.1007/s11104-020-04794-9

NASA POWER. (2025). *NASA Langley Research Center*. Recuperato da https://power.larc.nasa.gov

Nsarellah, N., Amamou, A., Taghouti, M., & Annicchiarico, P. (2011). Adaptation of Moroccan durum wheat varieties from different breeding eras. *Journal of Plant Breeding and Crop Science, 3*(2), 34–40. https://doi.org/10.5897/JPBCS.9000006

Ostergard, H., Finckh, M. R., Fontaine, L., Goldringer, I., Hoad, SP., Kristensen, K., van Bueren, E. T. L., Mascher, F., Munk, L., & Wolfe, M. S. (2009). Time for a shift in crop production: embracing complexity through diversity at all levels. *Journal of the Science of Food and Agriculture, 89*, 1439–1445. https://doi.org/10.1002/jsfa.3615

Preiti, G., Calvi, A., Giuffrè, A. M., Badagliacca, G., Virzì, N., & Bacchi, M. (2022). A comparative assessment of agronomic and baking qualities of modern/old varieties and landraces of wheat grown in Calabria (Italy). *Foods, 11*, Articolo 2359. https://doi.org/10.3390/foods11152359

Raggi, L., Ciancaleoni, S., Torricelli, R., Terzi, V., Ceccarelli, S., & Negri, V. (2017). Evolutionary breeding for sustainable agriculture: selection and multi-environment evaluation of barley populations and lines. *Field Crops Research, 204*, 76–88. https://doi.org/10.1016/j.fcr.2017.01.011

Rebetzke, G. J., Bonnett, D. G., & Ellis, M. H. (2012). Combining gibberellic acid-sensitive and insensitive dwarfing genes in breeding of higher-yielding, sesqui-dwarf wheats. *Field Crops Research, 127*, 17–25. https://doi.org/10.1016/j.fcr.2011.11.003

Rebetzke, G. J., Ellis, M. H., Bonnett, D. G., Condon, A. G., Falk, D., & Richards, R. A. (2011). The Rht13 dwarfing gene reduces peduncle length and plant height to increase grain number and yield of wheat. *Field Crops Research, 124*, 323–331. https://doi.org/10.1016/j.fcr.2011.06.022

Rebetzke, G. J., Ellis, M. H., Bonnett, D. G., Mickelson, B., Condon, A. G., & Richards, R. A. (2012). Height reduction and agronomic performance for selected gibberellin-responsive dwarfing genes in bread wheat (*Triticum aestivum* L.). *Field Crops Research, 126*, 87–96. https://doi.org/10.1016/j.fcr.2011.09.022

Reiss, E. R., & Drinkwater, L. E. (2018). Cultivar mixtures: a meta-analysis of the effect of intraspecific diversity on crop yield. *Ecological Applications, 28*, 62–78. https://doi.org/10.1002/eap.1629

Renard, D., & Tilman, D. (2019). National food production stabilized by crop diversity. *Nature, 571*, 257–260. https://doi.org/10.1038/s41586-019-1316-y

Royo, C., Soriano, J. M., & Alvaro, F. (2017). Wheat: a crop in the bottom of the Mediterranean diet pyramid. In *Mediterranean Identities - Environment, Society, Culture*. Rijeka, Croatia: InTech. https://doi.org/10.5772/intechopen.69184

Saha, B. C., Iten, L. B., Cotta, M. A., & Wu, Y. V. (2005). Dilute acid pretreatment, enzymatic saccharification and fermentation of wheat straw to ethanol. *Process Biochemistry, 40Trace*, 3693–3700. https://doi.org/10.1016/j.procbio.2005.04.006

Sahri, A., Chentoufi, L., Arbaoui, M., Ardisson, M., Belqadi, L., Birouk, A., Roumet, P., & Muller, H. (2014). Towards a comprehensive characterization of durum wheat landraces in Moroccan traditional agrosystems: analysing genetic diversity in the light of geography, farmers' taxonomy and tetraploid wheat domestication history. *BMC Evolutionary Biology, 14*, Articolo 264. https://doi.org/10.1186/s12862-014-0264-2

Salimi, M., Razavi, K. C., Amiri, M. N., Esmaeili, M., Khorramdel, S., Moghani, H., Grando, S., & Ceccarelli, S. (2023). Stability of agronomic traits of barley evolutionary populations under drought conditions in Iran. *Agronomy, 13*, Articolo 1931. https://doi.org/10.3390/agronomy13071931

Sanchez-Garcia, M., Álvaro, F., Peremarti, A., Martín-Sánchez, J. A., & Royo, C. (2015). Changes in bread-making quality attributes of bread wheat varieties cultivated in Spain during the 20th century. *European Journal of Agronomy, 63*, 79–88. https://doi.org/10.1016/j.eja.2014.11.006

Shlibak, A. A., Örgeç, M., & Zencirci, N. (2021). Wheat landraces versus resistance to biotic and abiotic stresses. In N. Zencirci, F. S. Baloch, E. Habyarimana, & G. Chung (A cura di), *Wheat Landraces* (pp. 193–214). Cham, Switzerland: Springer Nature.

Soliman, K. M., & Allard, R. W. (1991). Grain yield of composite cross populations of barley: effects of natural selection. *Crop Science, 31*(3), 705–708. https://doi.org/10.2135/cropsci1991.0011183X003100030032x

Spanic, V., Jukic, G., Zoric, M., & Varnica, I. (2023). Some agronomic properties of winter wheat genotypes grown at different locations in Croatia. *Agriculture, 14*, Articolo 4. https://doi.org/10.3390/agriculture14010004

Spina, A., Guarnaccia, P., Blangiforti, S., Giannone, V., Amato, C., Venora, G., Caruso, P., & Anastasi, U. (2017). Popolazioni locali siciliane di frumento tenero: caratteristiche bioagronomiche e qualitative. In *Atti dell'11° Convegno Aistec: I cereali per un sistema agroalimentare di qualità* (pp. 264–267). Roma, Italy: Associazione Italiana di Scienza e Tecnologia dei Cereali - AISTEC.

Stefan, L., Strebel, S., Camp, K. H., Christinat, S., Fossati, D., Städel, C., & Levy Häner, L. (2024). Multi-trait assessment of wheat variety mixtures performance and stability: mixtures for the win! *European Journal of Agronomy*. https://doi.org/10.1101/2024.07.22.604587

Taghouti, M., Nsarellah, N., Gaboun, F., & Rochdi, A. (2017). Multi-environment assessment of the impact of genetic improvement on agronomic performance and on grain quality traits in Moroccan durum wheat varieties of 1949 to 2017. *Global Journal of Plant Breeding and Genetics*, *4*, 394–404.

Talebnia, F., Karakashev, D., & Angelidaki, I. (2010). Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. *Bioresource Technology, 101*, 4744–4753. https://doi.org/10.1016/j.biortech.2009.11.080

Tomich, T. P., Brodt, S., Ferris, H., Galt, R., Horwath, W. R., Kebreab, E., Leveau, J. H., Liptzin, D., Lubell, M., Merel, P., et al. (2011). Agroecology: a review from a global-change perspective. *Annual Review of Environment and Resources, 36*, 193–222. https://doi.org/10.1146/annurev-environ-012110-121302

Turner, K. G., Lorts, C. M., Haile, A. T., & Lasky, J. R. (2020). Effects of genomic and functional diversity on stand-level productivity and performance of non-native Arabidopsis. *Proceedings of the Royal Society B: Biological Sciences, 287*, Articolo 20202041. https://doi.org/10.1098/rspb.2020.2041

Villa, T. C. C., Maxted, N., Scholten, M., & Ford-Lloyd, B. (2005). Defining and identifying crop landraces. *Plant Genetic Resources, 3*, 373–384. http://dx.doi.org/10.1079/PGR200591

Waines, J. G., & Ehdaie, B. (2007). Domestication and crop physiology: roots of Green-Revolution wheat. *Annals of Botany, 100*, 991–998. https://doi.org/10.1093/aob/mcm180

Wolfe, M. S., & Ceccarelli, S. (2020). The increased use of diversity in cereal cropping requires more descriptive precision. *Journal of the Science of Food and Agriculture, 100*(11), 4119–4123. https://doi.org/10.1002/jsfa.9906

Xynias, I. N., Mavromatis, A. G., Korpetis, E. G., Pankou, C. I., & Kozub, N. O. (2019). Description and characterization of Hellenic wheat germplasm for agronomical and seed quality parameters using phenotypical, biochemical and molecular approaches. *Cytology and Genetics, 53*, 337–347. https://doi.org/10.3103/S0095452719040108

Yu, M., Liu, Z. H., Yang, B., Chen, H., Zhang, H., & Hou, D. B. (2020). The contribution of photosynthesis traits and plant height components to plant height in wheat at the individual quantitative trait locus level. *Scientific Reports, 10*, Articolo 12261. https://doi.org/10.1038/s41598-020-69165-2

Zarkti, H., Ouabbou, H., Hilali, A., & Udupa, S. M. (2010). Detection of genetic diversity in Moroccan durum wheat accessions using agro-morphological traits and microsatellite markers. *African Journal of Agricultural Research, 5*, 1837–1844. https://doi.org/10.5897/AJAR09.249

Zeven, A. (1998). Landraces: a review of definitions and classifications. *Euphytica, 104*, 127–139. https://doi.org/10.1023/A:1018683119237

Zhang, Y., Xu, W., Wang, W., Dong, H., Qi, X., Zhao, M., Fang, Y., Gao, C., & Hu, L. (2016). Progress in genetic improvement of grain yield and related physiological traits of Chinese wheat in Henan Province. *Field Crops Research, 199*, 117–128. https://doi.org/10.1016/j.fcr.2016.09.022

Zheng, T. C., Zhang, X. K., Yina, G. H., Wanga, L. N., Hana, Y. L., Chen, L., Huang, F., Tang, J., Xia, X., & He, Z. (2011). Genetic gains in grain yield, net photosynthesis and stomatal conductance achieved in Henan Province of China between 1981 and 2008. *Field Crops Research, 122*, 225–233. https://doi.org/10.1016/j.fcr.2011.03.015