



ARTICLE

Performance, Stability, and Grain Quality of Tunisian Durum Wheat Landraces and Modern Cultivars under Organic Farming Conditions

Anis Boukrain* and Mondher Mejri

Laboratory of Functional Physiology and Valorization of Bio-Resources (LR23ES08), Higher Institute of Biotechnology of Beja, University of Jendouba, Beja, Tunisia

*Corresponding Author: Anis Boukrain. Email: anisboukrain@outlook.com

Received: 16 May 2026; Accepted: 21 September 2026; Published: 19 October 2026

ABSTRACT: The sustainability and quality of durum wheat under organic farming represent a major challenge in Mediterranean environments. This study evaluated the agronomic performance, yield stability, and technological quality of thirteen durum wheat genotypes (nine modern varieties and four local populations) grown under conventional farming and organic farming systems at two contrasting sites in Tunisia (Beja and Bousselem) over three consecutive seasons (2022–2024). Organic farming resulted in a significant reduction in grain yield, associated with a decrease in the number of grains per m² (–25.63%) and thousand-kernel weight (–14.86%). In 2022 and 2024, the average yield across sites was higher under conventional farming (up to 4212 kg·ha^{–1}) than under organic farming (up to 3042 kg·ha^{–1}). In contrast, during the dry year 2023, most genotypes performed better under organic farming. Stability analysis identified Monastir and INRAT100 as high-yielding and stable genotypes ($b_i \approx 1.0$). From a technological perspective, organic farming slightly improved test weight (+0.57%) and grain vitreousness (+1.07%), whereas protein content, wet gluten, and gluten index generally decreased, except for certain local populations such as Mahmoudi, which showed a notable increase in protein content (+8.76%). The correlation analysis revealed that grain yield was positively associated with the number of grains per m² ($r = 0.162$), but negatively correlated with semolina yield ($r = -0.405$). In contrast, vitreousness showed strong positive correlations with gluten-related and processing quality traits, particularly wet gluten ($r = 0.677$), dry gluten ($r = 0.750$), gluten index ($r = 0.757$), and semolina yield ($r = 0.742$). These findings highlight the importance of targeted varietal selection to reconcile productivity, yield stability, and technological quality of durum wheat under Mediterranean organic farming conditions.

KEYWORDS: Durum wheat; farming system; performance; stability; quality

1 Introduction

In the Mediterranean basin, durum wheat (*Triticum turgidum* L. ssp. *durum*, AABB, $2n = 4x = 28$) plays a strategic agronomic and nutritional role, as it is the primary raw material for semolina, pasta, and traditional products such as couscous and bulgur, which are key components of regional food security and cultural heritage [1,2]. In Tunisia, durum wheat is the dominant cereal crop and is mainly cultivated under rainfed conditions, characterized by strong interannual rainfall variability and frequent heat stress episodes during grain filling [3–5]. These agroclimatic constraints, which are expected to intensify under climate change, largely explain the chronic yield instability observed in the region [6–10].

In parallel with these constraints, demand for organically produced cereal products has increased steadily at both national and international levels [11,12]. The development of organic durum wheat

production combining high grain quality with adequate yield levels therefore represents a strategic lever to enhance the competitiveness of cereal value chains [13,14]. In this context, Tunisia possesses major agronomic assets, notably a rich varietal heritage that includes ancient durum wheat landraces recognized for their high protein content and superior technological quality, which are particularly suitable for sustainable farming systems [15]. The valorization of these genetic resources could contribute to reducing dependency on imports while promoting the export of high-value-added organic products [2,16].

Historically, improvements in durum wheat yield have relied on the intensification of farming systems, particularly through increased nitrogen fertilization and the adoption of modern high-yielding cultivars [17]. However, this strategy has been associated with progressive soil fertility degradation, low nitrogen use efficiency, and significant environmental impacts, raising concerns about the sustainability of conventional farming systems [18,19]. In this context, organic farming emerges as a credible alternative, particularly in Mediterranean low-input environments, although it imposes specific constraints that require appropriate varietal adaptation [20].

Several studies have demonstrated that cultivars selected under conventional farming conditions do not necessarily perform similarly under organic farming, where nitrogen availability is more limited and variable, and where physiological efficiency, stress tolerance, and competitive ability become decisive factors [21,22]. Consequently, varietal choice is a key determinant of success in organic durum wheat production, influencing both grain yield and quality [6]. Nevertheless, research specifically targeting the selection and evaluation of cultivars adapted to organic farming systems remains limited, particularly under Mediterranean conditions [11].

Beyond grain yield, technological quality is a critical criterion for the valorization of organic durum wheat [23]. Grain quality depends on a set of traits closely related to grain structure and composition, including vitreousness, protein content, and gluten properties, which directly determine semolina yield and processing aptitude [3]. The relationships between yield and quality are often complex and sometimes antagonistic, and are strongly influenced by genotype, farming system, and their interactions, highlighting the need for integrated assessment approaches [24].

In this context, durum wheat landraces, long marginalized in favor of modern high-yielding cultivars, have regained interest due to their adaptation to local agroclimatic conditions, yield stability, and specific quality attributes, particularly high protein content and favorable endosperm structure [25]. Conversely, modern cultivars generally exhibit higher productivity, but their yield stability and technological performance under organic farming remain insufficiently documented [26]. Yield stability analysis across multiple growing seasons is therefore essential to identify genotypes capable of maintaining consistent performance under variable environmental conditions [2,27]. Stability approaches based on genotype responses to environmental variation allow the identification of cultivars that optimally balance productivity, stability, and quality, which is a fundamental requirement for sustainable organic farming systems [28].

Accordingly, the present study aims to provide an integrated evaluation of agronomic performance, yield stability, and grain technological quality of thirteen durum wheat varieties, including nine modern cultivars and four local landraces, grown under conventional farming and organic farming systems over three consecutive growing seasons. The specific objectives were to: (i) assess the effect of farming system on grain yield and its components; (ii) evaluate interannual yield stability; and (iii) characterize the impact of farming system on key technological quality traits, including grain moisture content, test weight, vitreousness, protein content, wet gluten, dry gluten, gluten index, and semolina yield.

2 Materials and Methods

2.1 Plant Material

The plant material involved in this research comprised thirteen durum wheat varieties, which are representative of the durum wheat populations cultivated in Tunisia throughout the 20th century (Table 1). These varieties reflect a wide genetic diversity and are categorized into two main groups: local varieties ($n = 4$) and modern varieties ($n = 9$). Modern cultivars were obtained from the Regional Center for Research in Field Crops of Beja (CRRGC Beja), as well as from selected seed companies, including the Central Cooperative of Selected Seeds and Plants (CCSPS), the Society of Selected Seeds (SOSEM), and the Central Mutual Seed Company (COSEM), whereas landraces were sourced from the Tunisian National Gene Bank (BNG) and local farmers. Their selection aimed to assess their potential responses under an organic farming system. The specific characteristics of each genotype are detailed in Table 1 below.

Table 1: Origin, year of registration, and main characteristics of the thirteen durum wheat genotypes studied [29–34].

Genotypes	Origin	Registration Date	Main Characteristics
Karim	INRAT/CIMMYT	1980	Fairly resistant to septoria and brown rust.
Razzak	INRAT-Tunisia	1987	Very productive cultivar (25% more than Karim), resistant to powdery mildew and fairly resistant to septoria and brown rust.
Khiar	INRAT/CIMMYT	1992	Cultivars that are productive and relatively susceptible to brown rust and septoria diseases.
Maali	INRAT-Tunisia	2007	Resistant to powdery mildew and fairly resistant to septoria and brown rust.
Salim	INRAT-Tunisia	2009	High yield, resistance to septoria, yellow rust, and brown rust.
INRAT100	CIMMYT/Tunisia	2017	Cultivars that are productive, resistance to septoria, yellow rust, and brown rust, and drought tolerance.
Dhahbi	INRAT-Tunisia	2018	Productive, resistant cultivar to powdery mildew and yellow rust and very high semolina quality.
Monastir	SOSEM	2012	Cultivars that are productive, resistant to septoria and brown rust, and tolerant to drought.
Saragolla	Italy	2004	High yield, resistance to septoria and rust.
Chili	French (old variety/landrace)	1932	Medium performance, resistance to septoria and yellow rust.
Biskri	Algeria (old variety/landrace)	1909	Medium performance, drought tolerance and very high semolina quality.
Mahmoudi	Tunisia (old variety/landrace)	1893	Medium performance, drought tolerance and very high semolina quality.
Jenah Khotifa	Tunisia (old variety/landrace)	1915	Medium performance, resistance to septoria and yellow rust.

CIMMYT: International Maize and Wheat Improvement Centre; INRAT: National Institute of Agricultural Research of Tunisia; SOSEM: Selected Seeds Company.

2.2 Experimental Site

The comparative evaluation of durum wheat varieties was conducted under field conditions over three consecutive cropping seasons (2021–2022, 2022–2023, and 2023–2024) at two distinct experimental sites. The first site is the Gnadil experimental station in Beja, located in a sub-humid zone and characterized by clay-loam to clay-sandy loam soils, slightly alkaline in reaction ($\text{pH} \approx 7.2$), with variable annual precipitation estimated at approximately 563 mm in 2022, 414 mm in 2023, and 528 mm in 2024. The second site corresponds to the INGC intervention station located in Bousselem, within the upper semi-arid bioclimatic zone, with clay-sandy loam soils, a higher $\text{pH} (\approx 8.1)$, and moderate but fluctuating annual rainfall of about 501 mm in 2022, 365 mm in 2023, and 480 mm in 2024. Both locations share a Mediterranean climate, characterized by cold winters and extremely hot, dry summers. It is worth noting that these two plots have not been treated with synthetic chemical products for at least three years, in accordance with the requirements of organic farming specifications (Fig. 1).

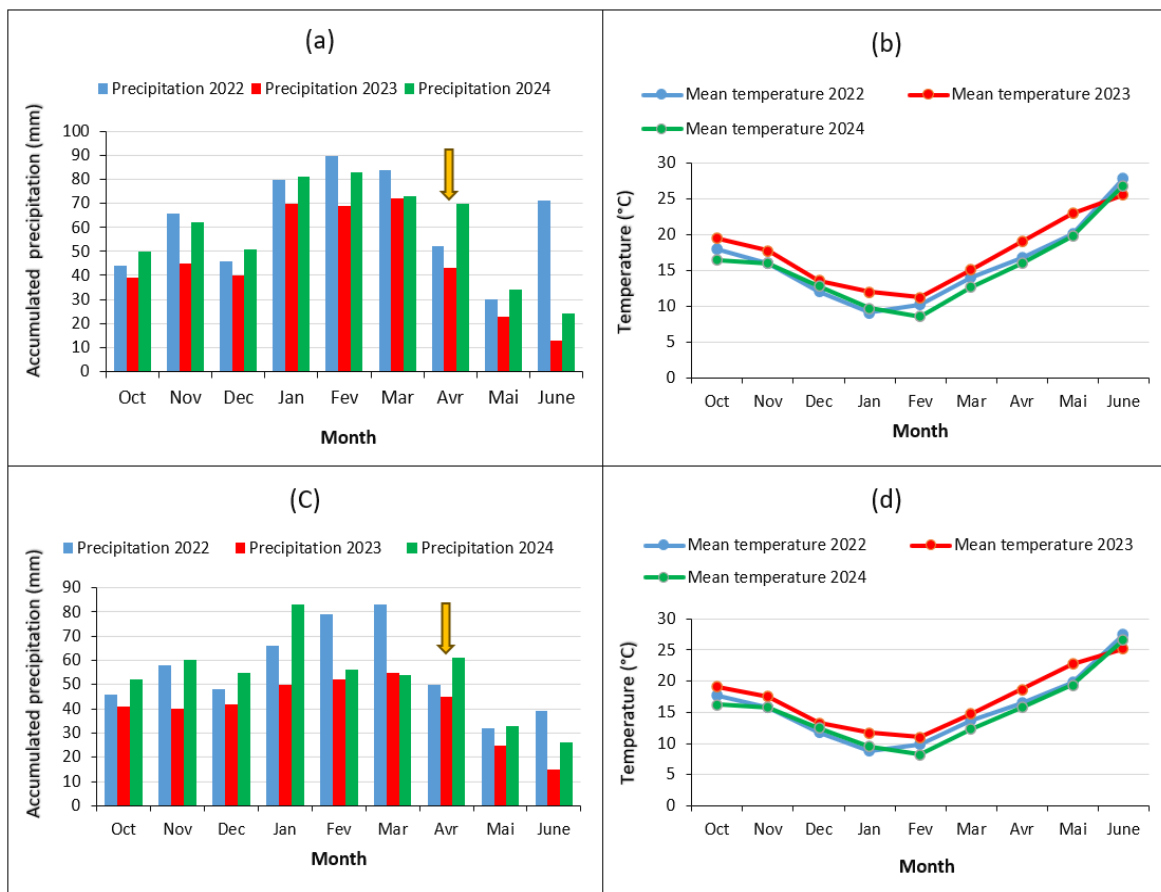


Figure 1: Climatic data recorded during the three consecutive cropping seasons (2021–2022, 2022–2023, and 2023–2024) at the two experimental sites. (a) Monthly distribution of accumulated precipitation in Beja; (b) Monthly mean air temperature in Beja; (c) Monthly distribution of accumulated precipitation in Bousselem; (d) Monthly mean air temperature in Bousselem; ↓ grain filling period.

All analyses were performed on clay-loam and clay-sandy-loam soils, both identified as Vertisols. Fig. 2 summarizes the key characteristics of the experimental sites, including geographical location, GPS coordinates, bioclimatic classification, soil texture, and pH. Notably, in compliance with organic farming

standards, both plots had been free of any synthetic chemical inputs for a minimum period of three years prior to the onset of the trial.

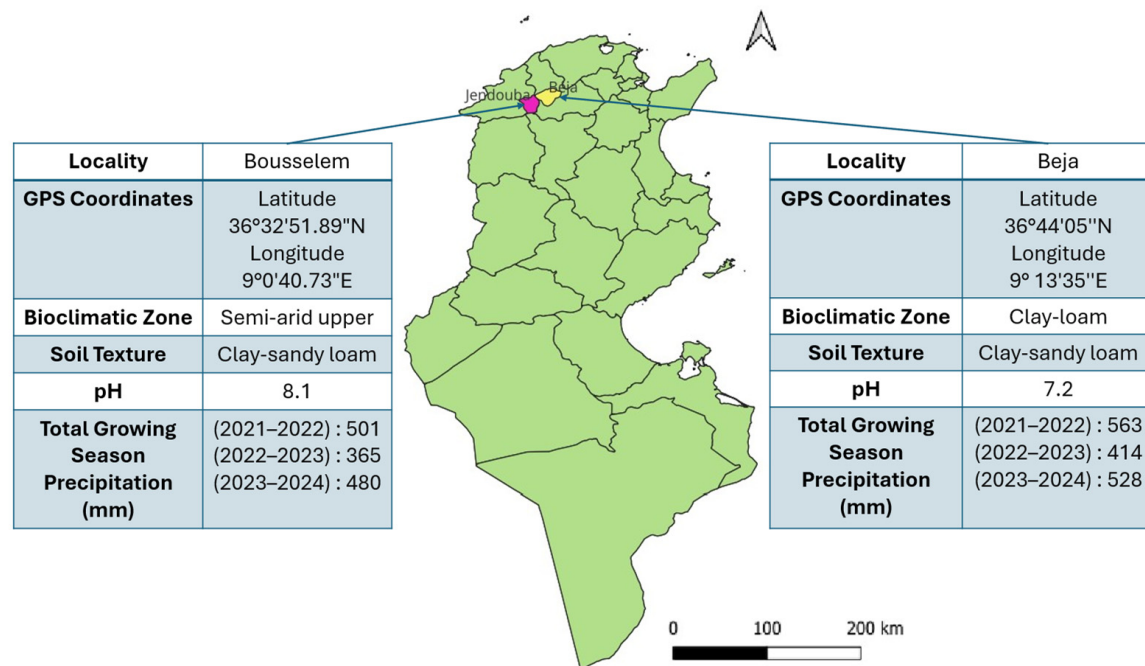


Figure 2: Geographical location of the experimental sites of Beja and Bousselem (northwestern Tunisia) and their main agro-climatic and edaphic characteristics, including GPS coordinates, bioclimatic zone, soil texture, pH, and total growing season precipitation over the 2021–2024 cropping seasons.

2.3 Experimental Design and Management

The experimental design used during the three years of study followed a split-plot design with three replications. The main factor was the farming system (organic vs. conventional), while the variety, randomized within each treatment, represented the secondary factor. Each replication was subdivided into two parts, one for conventional farming and the other for organic farming, with elementary plots of 3 m × 1 m, subdivided into six rows spaced 20 cm apart. The total area of the experiment was 234 m². During the three years of the study, durum wheat was preceded by a fallow period to ensure that the results obtained were not influenced by previous crops. The same condition was applied to both experimental sites. Soil preparation operations included moderate plowing using an offset pulverizer, followed by the burial of plant residues, and then seedbed preparation using cultivators and a harrow. The sowing, carried out at 600 seeds per elementary plot, took place each year in the second half of November, corresponding to an average sowing rate of 120 kg/ha. Weed control was ensured by a stubble cultivation followed by false sowing, with control methods differentiated according to the cultivation method. For the organic plots, mechanical weeding using a rotavator and manual weeding using a rake and hoe were performed, while for the conventional plots, chemical weeding was carried out by spraying with a backpack sprayer, using Granstar at a rate of 20 g/ha. Regarding fertilization, nitrogen was applied in the form of ammonium nitrate (33.5% N) for the conventional plots in three fractions (30%, 40%, and 30%), totaling 150 kg N·ha⁻¹, with the first fraction after emergence, the second at the beginning of tillering, and the third at the second node stage, this difference in nitrogen availability compared with the organic treatment (≈0.6 kg N·ha⁻¹ via liquid organic fertilizer) potentially influencing crop growth and yield. For the organic plots, a liquid

organic nitrogen fertilizer containing 5.9% organic nitrogen, 22.2% organic carbon, and 36.9% amino acids was applied at a rate of $2 \text{ L}\cdot\text{ha}^{-1}$, five applications after emergence spaced 10 days apart during the growing period. Finally, no phytosanitary protection methods were applied against fungal diseases or insects during the entire experimental period.

2.4 Agronomic Performance of Tested Genotypes

The agronomic performance of the tested genotypes was assessed using a comprehensive set of phenological traits measured at the key stages of the crop growth cycle. Plant stand density, expressed as the number of emerged plants per square meter ($\text{plants}\cdot\text{m}^{-2}$), was determined at the emergence stage (three-leaf stage) by exhaustively counting all plants within a 1 m^2 quadrat placed in each experimental plot. Plant height (PH, cm) was measured at physiological maturity using a graduated ruler, from the collar to the tip of the spike awns, on ten randomly selected plants per plot in order to characterize vegetative growth among genotypes.

The number of spikes per square meter ($\text{spikes}\cdot\text{m}^{-2}$) was recorded at the grain formation stage by counting all spikes within a randomly placed 1 m^2 quadrat in each plot. The number of grains per spike ($\text{grains}\cdot\text{spike}^{-1}$) was determined at physiological maturity by counting the average number of grains from a representative sample of 25 spikes per plot, while the number of grains per square meter ($\text{grains}\cdot\text{m}^{-2}$) was estimated as the product of spike density and the mean number of grains per spike.

Thousand-grain weight (TGW, g) was measured in accordance with the Tunisian standard N.T. 51.29 (2012), using 1000 grains counted with a Numigral photoelectric grain counter, to assess grain filling. Total aboveground biomass, expressed in kilograms per hectare ($\text{BIO}, \text{kg}\cdot\text{ha}^{-1}$), was determined at maturity by harvesting plant material from a one-meter linear section in each plot and extrapolating the values to a hectare basis.

The harvest index (HI, %) was calculated for each variety and farming system as the ratio of grain yield to total aboveground biomass, providing an estimate of dry matter partitioning efficiency toward reproductive organs. Finally, grain yield ($\text{kg}\cdot\text{ha}^{-1}$) was determined at harvest in June using a plot combine harvester, and expressed in kilograms per hectare based on the grain weight obtained from each experimental plot.

2.5 Analysis of Stability Parameters

The regression coefficient (b_i) represents the response of a genotype to the environmental index, which is calculated based on the average performance of all genotypes in each environment [35]. If b_i does not differ significantly from 1, the genotype is considered well adapted to all environments. In addition, the variance of the deviations from regression (S^2_{di}) is one of the most widely used parameters for evaluating genotype stability. A value of S^2_{di} equal to zero ($S^2_{di} = 0$) indicates perfect stability, whereas a positive value ($S^2_{di} > 0$) reflects greater instability across environments. Thus, genotypes with the lowest S^2_{di} values are the most desirable for their stability [36].

The coefficient of variation (CV_i) was proposed as a stability indicator, in combination with mean yield and environmental variance (EV) [37]. The most desirable genotypes are those that exhibit low CV_i , low EV, and high average yield. Furthermore, Wricke introduced the concept of ecovalence, defined as the contribution of each genotype to the sum of squares of the genotype $\times$ environment interaction (GEI) [38]. The ecovalence (W_i^2) of a genotype corresponds to the sum of squares of its interactions with the environments. Genotypes with lower W_i^2 values deviate less from the mean across environments and are therefore considered more stable. The stability variance, calculated as the residual variance of the

genotype across environments after removing the main effects of environmental means, was also proposed as a stability parameter [39].

Genotypes with minimal stability variance are regarded as more stable. Stability has also been quantified based on the variance component of genotype $\times$ environment interactions for each possible pair of genotypes, where the average of these estimates for a given genotype (θ_i) serves as a measure of stability; lower θ_i values indicate greater stability [40]. Thus, the lower the θ_i value, the more stable the genotype is considered. The superiority index (P_i) measures the average deviation of a genotype's yield from that of the best-performing genotype in each environment, with lower P_i values indicating greater stability and performance [41]. Genotypes with lower P_i values are considered the most stable and high-performing. Finally, the geometric adaptability index (GAI), based on the geometric mean of yields, can be used to assess genotype adaptability. Genotypes with the highest GAI values are regarded as the most stable and best adapted to a wide range of environments.

2.6 Grain Quality Evaluation

Grain moisture content and test weight (hectolitre weight) were measured using an electronic Dickey-John moisture meter, which allows the simultaneous determination of grain moisture, bulk density, and temperature. All measurements were performed using instruments previously calibrated against standardized reference methods, in accordance with the ISO 712:2009 [42] for the gravimetric determination of moisture content and ISO 7971-3:2019 for the determination of cereal test weight [43]. Grain vitreousness (VitA) was determined according to EN 15585:2008, based on the determination of the percentage of vitreous grains and the calculation of the percentage of vitreous grains [44]. Protein content was determined according to the AFNOR standard method NF V03-050 using the Kjeldahl method [45]. Wet gluten content and gluten index were measured in accordance with ISO 21415-2:2015 [46] using an automatic Glutomatic system (Glutomatic 2200, Perten Instruments, Sweden); the fraction retained on the sieve after wet gluten extraction was centrifuged (6000 ± 5 rpm) and weighed to calculate the gluten index, while dry gluten content was obtained by rapid drying of wet gluten according to ISO 21415-3:2006 [47]. Finally, mean semolina yield (MSY) was determined after experimental milling of the grain, following standardized experimental milling procedures in accordance with ISO 15793:2000 [48].

2.7 Statistical Analysis

The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 27; IBM Corp., Armonk, NY, USA). For each experimental year, an analysis of variance (ANOVA) was conducted separately for each site using the General Linear Model (GLM) procedure to assess the effects of the farming system (organic farming vs. conventional farming), variety ($n = 13$), and their interaction. When significant effects were detected, mean comparisons were performed using Tukey's post hoc test. A combined ANOVA was subsequently carried out to evaluate the significance of differences among varieties, sites, farming systems, and years, as well as their first-, second-, and third-order interactions. In addition, stability analyses of agronomic traits were performed using the online software STABILITYSOFT (developed by the Seed and Plant Improvement Institute, Iran), which allows the estimation of parametric stability statistics [49]. Finally, for grain nutritional quality traits, a two-factor combined ANOVA was applied to determine the effects of the farming system, variety, and their interaction. Principal Component Analysis (PCA) was performed using XLSTAT 2019.2.2 (Addinsoft, Paris, France) based on the correlation matrix, which standardizes the variables prior to analysis. Data are presented as mean $\pm$ standard deviation (SD).

3 Results

3.1 Agronomic Traits and Yield Components

The statistical analysis of agronomic traits and yield components over the three experimental years is presented in Tables 2 and S1. Plant density (plants m^{-2}) was significantly affected by the farming system ($p < 0.001$), with values ranging under conventional farming from 197 plants m^{-2} (Jenah Khotifa) to 222 plants m^{-2} (Maali), and under organic farming from 179 plants m^{-2} (Jenah Khotifa) to 198 plants m^{-2} (Monastir) (Table 2). Overall, mean plant density decreased from 209.54 plants m^{-2} under conventional farming to 189.15 plants m^{-2} under organic farming, corresponding to a reduction of 9.73%. In line with this vegetative response, plant height was also strongly influenced by the farming system ($p < 0.001$), ranging from 100 cm (Karim) to 120 cm (Maali) under conventional farming and from 85 cm (Chili) to 108 cm (Biskri) under organic farming (Table 2), with a decline in the overall mean from 108.69 cm to 98.54 cm (−9.34%). Similarly, the number of spikes per m^2 was significantly affected by the farming system ($p < 0.001$), varying from 288 spikes m^{-2} (Khlar) to 349 spikes m^{-2} (Monastir) under conventional farming, and from 261 spikes m^{-2} (Maali) to 314 spikes m^{-2} (Mahmoudi) under organic farming (Table 2), with a decrease in the general mean from 318.08 to 280.69 spikes m^{-2} (−11.75%). This trend extended to yield components, as the number of grains per spike was significantly reduced under organic farming ($p < 0.001$), ranging from 30.23 (Chili) to 47.33 grains spike $^{-1}$ under conventional farming and from 30.05 (Chili) to 35.80 grains spike $^{-1}$ under organic farming (Table 2), resulting in a decrease in the overall mean from 38.22 to 31.88 grains spike $^{-1}$. Consequently, the number of grains per m^2 showed a highly significant difference between farming systems ($p < 0.001$), ranging from 10,576.46 grains m^{-2} (Jenah Khotifa) to 13,631.05 grains m^{-2} (Khlar) under conventional farming and from 8371.50 grains m^{-2} (Razzak) to 9881.58 grains m^{-2} (Mahmoudi) under organic farming (Table 2), with a marked reduction in the general mean from 12,012.76 to 8935.39 grains m^{-2} (−25.63%). In addition, thousand grain weight (TKW) was significantly affected by the farming system ($p < 0.001$), with values ranging from 46.95 g (Dhahbi) to 59.12 g (Mahmoudi) under conventional farming and from 40.08 g (Khlar) to 52.18 g (Biskri) under organic farming (Table 2), corresponding to a decrease in the mean from 53.03 g to 45.15 g (−14.86%). By contrast, aboveground biomass was not significantly influenced by the farming system ($p > 0.05$), showing a limited variation from 4639 $\text{kg}\cdot\text{ha}^{-1}$ under conventional farming to 4478 $\text{kg}\cdot\text{ha}^{-1}$ 44.78 $\text{q}\cdot\text{ha}^{-1}$ under organic farming (−3.47%). Finally, the harvest index was significantly affected by the farming system ($p < 0.001$), with the mean value declining from 0.65 under conventional farming to 0.56 under organic farming, corresponding to a reduction of 13.85% (Table 2).

3.2 Grain Yield

The analysis of data collected over three experimental years (2022–2024) at the two study sites revealed that the farming system, genotype, and their interaction had a highly significant effect on grain yield ($p < 0.001$) (Table 3; Tables S2 and S3). Overall, mean grain yield was higher under conventional farming than under organic farming.

In 2022, cumulative rainfall during the growing season (563 mm) was close to the regional average (620 mm). At both sites, mean grain yield was higher under conventional farming than under organic farming. At Beja, yield decreased from 4212 $\text{kg}\cdot\text{ha}^{-1}$ under conventional farming to 3042 $\text{kg}\cdot\text{ha}^{-1}$ under organic farming, while at Bousselem it declined from 3878 to 2937 $\text{kg}\cdot\text{ha}^{-1}$, corresponding to reductions of 27.7% and 24.3%, respectively. A marked varietal variability was observed: Dhahbi recorded the highest yield under conventional farming (4906 $\text{kg}\cdot\text{ha}^{-1}$), whereas Karim showed the lowest yield (3380 $\text{kg}\cdot\text{ha}^{-1}$). Under organic farming, Monastir and Dhahbi outperformed the other varieties (Table 3).

Table 2: Yield-related traits of 13 durum wheat varieties grown at two sites under two farming systems over three experimental years.

	Plants m ⁻²		Plant Height (cm)		Spikes m ⁻²		Grains Spike ⁻¹		Grains m ⁻²		TGW (g)		Biomass Yield (Kg·ha ⁻¹)		HI	
Varieties	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF
Karim	211 ± 1.00 ^a	195 ± 3.00 ^b	100 ± 1.00 ^a	97 ± 2.00 ^a	296 ± 2.00 ^a	274 ± 1.00 ^b	44.00 ± 0.03 ^a	31.44 ± 0.00 ^b	13,024.04 ± 96.88 ^a	8614.56 ± 31.44 ^b	50.22 ± 0.03 ^a	44.39 ± 0.00 ^b	3812 ± 12.37 ^b	4518 ± 9.31 ^a	0.68 ± 0.00 ^a	0.52 ± 0.01 ^b
Razzak	206 ± 0.00 ^a	175 ± 1.00 ^b	103 ± 0.00 ^a	98 ± 1.00 ^b	320 ± 0.00 ^a	278 ± 1.00 ^b	36.71 ± 0.00 ^a	30.11 ± 0.00 ^b	11,747.20 ± 0.00 ^a	8370.58 ± 30.11 ^b	52.14 ± 0.00 ^a	48.60 ± 0.00 ^b	4184 ± 13.41 ^a	4361 ± 9.67 ^a	0.62 ± 0.00 ^a	0.54 ± 0.00 ^b
Khlar	214 ± 2.00 ^a	193 ± 0.00 ^b	115 ± 1.00 ^a	102 ± 0.00 ^b	288 ± 1.00 ^a	270 ± 0.00 ^b	47.33 ± 0.01 ^a	32.70 ± 0.05 ^b	13,631.05 ± 50.21 ^a	8829.00 ± 13.50 ^b	58.77 ± 0.00 ^a	40.08 ± 0.00 ^b	4749 ± 18.95 ^a	4695 ± 10.69 ^a	0.70 ± 0.01 ^a	0.59 ± 0.00 ^b
Maali	222 ± 0.00 ^a	196 ± 0.00 ^b	120 ± 1.00 ^a	94 ± 1.00 ^b	292 ± 1.00 ^a	261 ± 2.00 ^b	45.80 ± 0.01 ^a	35.80 ± 0.02 ^b	13,373.61 ± 48.72 ^a	9343.83 ± 76.82 ^b	56.89 ± 0.00 ^a	45.52 ± 0.01 ^b	4791 ± 16.06 ^a	4591 ± 9.79 ^a	0.69 ± 0.00 ^a	0.58 ± 0.02 ^b
Salim	215 ± 1.00 ^a	187 ± 1.00 ^b	113 ± 2.00 ^a	89 ± 0.00 ^b	304 ± 3.00 ^a	285 ± 2.00 ^b	41.36 ± 0.01 ^a	30.44 ± 0.00 ^b	12,573.46 ± 127.12 ^a	8674.45 ± 60.87 ^b	55.28 ± 0.00 ^a	41.91 ± 0.00 ^b	4523 ± 16.04 ^a	4138 ± 6.64 ^a	0.67 ± 0.02 ^a	0.59 ± 0.00 ^b
INRAT100	209 ± 1.00 ^a	189 ± 1.00 ^b	111 ± 0.00 ^a	105 ± 1.00 ^b	318 ± 0.00 ^a	267 ± 0.00 ^b	37.25 ± 0.01 ^a	33.66 ± 0.00 ^a	11,845.50 ± 3.18 ^a	8987.22 ± 0.00 ^b	53.50 ± 0.01 ^a	43.77 ± 0.00 ^b	4841 ± 17.97 ^a	4743 ± 9.12 ^a	0.67 ± 0.00 ^a	0.57 ± 0.01 ^b
Dhahbi	210 ± 0.00 ^a	192 ± 0.00 ^b	116 ± 1.00 ^a	101 ± 0.00 ^b	290 ± 0.00 ^a	270 ± 3.00 ^b	46.66 ± 0.01 ^a	32.60 ± 0.01 ^b	13,531.40 ± 2.90 ^a	8802.02 ± 100.50 ^b	46.95 ± 0.00 ^a	48.23 ± 0.00 ^a	4907 ± 14.22 ^a	4513 ± 12.01 ^a	0.74 ± 0.00 ^a	0.64 ± 0.00 ^b
Monastir	208 ± 0.00 ^a	198 ± 2.00 ^b	101 ± 0.00 ^a	103 ± 1.00 ^a	349 ± 0.00 ^a	279 ± 1.00 ^b	30.40 ± 0.02 ^a	32.09 ± 0.03 ^a	10,609.60 ± 6.98 ^a	8953.13 ± 40.46 ^b	49.04 ± 0.00 ^a	42.14 ± 0.01 ^b	4645 ± 18.57 ^a	4566 ± 1.06 ^a	0.62 ± 0.02 ^a	0.57 ± 0.00 ^b
Saragolla	205 ± 1.00 ^a	193 ± 0.00 ^b	113 ± 1.00 ^a	99 ± 1.00 ^b	309 ± 4.00 ^a	277 ± 0.00 ^b	39.80 ± 0.00 ^a	30.45 ± 0.00 ^b	12,298.20 ± 159.20 ^a	8434.65 ± 0.00 ^b	54.86 ± 0.00 ^a	48.97 ± 0.00 ^b	5277 ± 12.13 ^a	4371 ± 7.64 ^b	0.60 ± 0.00 ^a	0.51 ± 0.00 ^b
Chili	206 ± 0.00 ^a	181 ± 0.00 ^b	106 ± 1.00 ^a	85 ± 0.00 ^b	353 ± 0.00 ^a	301 ± 2.00 ^b	30.23 ± 0.00 ^a	30.05 ± 0.01 ^a	10,668.67 ± 783.83 ^a	9043.85 ± 294.83 ^b	49.71 ± 0.00 ^a	44.37 ± 0.00 ^b	4683 ± 14.04 ^a	4248 ± 11.51 ^a	0.59 ± 0.00 ^a	0.55 ± 0.00 ^a
Biskri	208 ± 0.00 ^a	191 ± 0.00 ^b	107 ± 0.00 ^a	108 ± 0.00 ^a	325 ± 1.00 ^a	287 ± 0.00 ^b	35.33 ± 0.00 ^a	33.20 ± 0.00 ^a	11,482.25 ± 35.33 ^a	9528.40 ± 0.00 ^b	53.27 ± 0.00 ^a	52.18 ± 0.00 ^a	4528 ± 15.21 ^a	4657 ± 6.56 ^a	0.63 ± 0.00 ^a	0.58 ± 0.01 ^b
Mahmoudi	213 ± 1.00 ^a	190 ± 0.00 ^b	103 ± 0.00 ^a	104 ± 0.00 ^a	343 ± 1.00 ^a	314 ± 3.00 ^b	31.50 ± 0.00 ^a	31.47 ± 0.00 ^a	10,804.50 ± 31.50 ^a	9881.58 ± 94.41 ^b	59.12 ± 0.00 ^a	40.61 ± 0.00 ^b	4758 ± 15.91 ^a	4652 ± 9.97 ^a	0.64 ± 0.00 ^a	0.48 ± 0.00 ^b
Jenah Khotifa	197 ± 0.00 ^a	179 ± 1.00 ^b	105 ± 0.00 ^a	96 ± 1.00 ^b	348 ± 0.00 ^a	286 ± 0.00 ^b	30.44 ± 0.00 ^a	30.41 ± 0.00 ^a	10,576.46 ± 2449.33 ^a	8696.75 ± 776.78 ^b	49.69 ± 0.00 ^a	46.15 ± 0.00 ^a	4604 ± 19.87 ^a	4163 ± 9.97 ^a	0.62 ± 0.01 ^a	0.53 ± 0.01 ^b
Mean	209.54 ± 5.85^a	189.15 ± 6.81^b	108.69 ± 6.24^a	98.54 ± 6.34^b	318.08 ± 23.35^a	280.69 ± 14.06^b	38.22 ± 6.28^a	31.88 ± 1.65^b	12,012.76 ± 1266.62^a	8935.39 ± 464.85^b	53.03 ± 3.74^a	45.15 ± 3.50^b	4639 ± 13.62^a	4478 ± 7.85^a	0.65 ± 0.04^a	0.56 ± 0.04^b
ANOVA																
FS	***		***		***		***		***		***		NS		***	
Variety	***		***		***		***		***		***		NS		***	
FS * Variety	***		***		***		***		***		***		NS		***	

Values are expressed as mean ± standard deviation (n = 3). Different letters within the same row indicate statistically significant differences ($p \leq 0.05$, Tukey's test). *** indicates a significant difference at $p < 0.001$, whereas NS indicates a non-significant difference ($p > 0.05$). FS: farming system; CF: conventional farming; OF: organic farming; Plants m⁻²: plant density; spikes m⁻²: number of spikes per square meter; grains spike⁻¹: number of grains per spike; grains m⁻²: number of grains per square meter; TGW: thousand grain weight; biomass yield: aboveground biomass yield; HI: harvest index.

Table 3: Grain yield (kg·ha⁻¹) of thirteen durum wheat varieties grown at two sites (Beja and Bousselem) under conventional and organic farming systems over three experimental years (2022–2024).

Varieties	Experimental Year 2022				Experimental Year 2023				Experimental Year 2024			
	Beja		Bousselem		Beja		Bousselem		Beja		Bousselem	
	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF
Karim	3380 ± 0.40 ^a	2800 ± 0.50 ^b	3060 ± 1.40 ^a	2835 ± 1.03 ^b	1777 ± 1.17 ^b	2080 ± 1.54 ^a	1495 ± 0.25 ^b	1757 ± 1.65 ^a	2970 ± 1.18 ^a	2250 ± 1.83 ^b	2870 ± 3.56 ^a	2350 ± 3.12 ^b
Razzak	3485 ± 0.15 ^a	2906 ± 0.31 ^b	2980 ± 0.50 ^a	2865 ± 0.75 ^b	1767 ± 1.33 ^b	1972 ± 1.19 ^a	1542 ± 1.20 ^b	1712 ± 1.20 ^a	3010 ± 4.83 ^a	2180 ± 1.65 ^b	2780 ± 2.23 ^a	2495 ± 2.11 ^b
Khiar	4643 ± 2.95 ^a	3680 ± 0.40 ^b	4048 ± 0.63 ^a	3235 ± 1.25 ^b	1943 ± 1.17 ^b	2482 ± 0.85 ^a	1747 ± 0.61 ^b	1955 ± 1.25 ^a	4140 ± 2.26 ^a	2690 ± 1.05 ^b	3405 ± 2.69 ^a	2580 ± 2.59 ^b
Maali	4555 ± 0.85 ^a	3370 ± 1.10 ^b	3995 ± 0.15 ^a	3006 ± 0.76 ^b	2117 ± 0.76 ^b	2660 ± 1.00 ^a	2078 ± 1.78 ^b	2280 ± 1.50 ^a	3415 ± 4.87 ^a	2410 ± 2.74 ^b	3675 ± 1.74 ^a	2175 ± 0.80 ^b
Salim	4205 ± 0.75 ^a	2630 ± 1.05 ^b	3790 ± 0.70 ^a	3150 ± 0.95 ^b	2133 ± 1.40 ^b	2320 ± 1.10 ^a	1810 ± 1.32 ^b	2010 ± 1.10 ^a	3285 ± 2.97 ^a	1880 ± 1.59 ^b	2890 ± 1.71 ^a	2660 ± 1.06 ^b
INRAT100	4775 ± 0.98 ^a	3361 ± 2.40 ^b	4280 ± 0.50 ^a	3063 ± 1.43 ^b	2103 ± 1.88 ^b	2830 ± 1.25 ^a	2173 ± 0.70 ^b	2353 ± 0.61 ^a	3200 ± 2.91 ^a	2130 ± 2.55 ^b	2930 ± 2.70 ^a	2445 ± 3.04 ^b
Dhahbi	4906 ± 1.45 ^a	4088 ± 1.70 ^b	4643 ± 1.23 ^a	3446 ± 1.35 ^b	2927 ± 0.70 ^a	2375 ± 0.85 ^b	2484 ± 0.91 ^a	2317 ± 1.72 ^b	3740 ± 2.25 ^a	2510 ± 1.87 ^b	3085 ± 3.63 ^a	2595 ± 2.98 ^b
Monastir	4162 ± 0.68 ^a	2213 ± 1.94 ^b	3985 ± 1.03 ^a	2905 ± 1.03 ^b	2280 ± 2.61 ^b	2888 ± 1.47 ^a	2100 ± 1.40 ^b	2340 ± 1.40 ^a	2010 ± 0.36 ^b	3145 ± 0.78 ^a	2615 ± 3.23 ^a	2216 ± 1.50 ^b
Saragolla	4127 ± 1.12 ^a	2633 ± 1.25 ^b	3656 ± 0.97 ^a	2433 ± 1.16 ^b	2533 ± 0.61 ^a	2030 ± 1.05 ^b	2340 ± 0.79 ^a	1550 ± 1.14 ^b	3320 ± 1.87 ^a	2300 ± 2.61 ^b	3020 ± 2.21 ^a	2430 ± 1.57 ^b
Chili	4165 ± 0.85 ^a	3160 ± 1.87 ^b	3605 ± 1.05 ^a	2755 ± 0.85 ^b	2077 ± 1.30 ^b	2315 ± 1.75 ^a	1638 ± 1.38 ^b	1975 ± 1.85 ^a	2570 ± 1.31 ^a	1940 ± 2.67 ^b	2745 ± 2.96 ^a	1751 ± 0.64 ^b
Biskri	3642 ± 1.27 ^a	3145 ± 1.21 ^b	4240 ± 1.40 ^a	3061 ± 1.16 ^b	2262 ± 1.48 ^b	2675 ± 1.05 ^a	2012 ± 1.58 ^b	2370 ± 1.00 ^a	2070 ± 2.75 ^b	2785 ± 2.11 ^a	2890 ± 1.35 ^a	2240 ± 2.26 ^b
Mahmoudi	4315 ± 1.15 ^a	2958 ± 1.38 ^b	3970 ± 1.10 ^a	2600 ± 1.10 ^b	2337 ± 1.67 ^a	2060 ± 1.11 ^b	1927 ± 1.33 ^b	2005 ± 1.55 ^a	3020 ± 2.86 ^a	1950 ± 2.59 ^b	2700 ± 1.30 ^a	1825 ± 1.29 ^b
Jenah Khotifa	4390 ± 0.80 ^a	2595 ± 0.65 ^b	4155 ± 0.95 ^a	2825 ± 2.32 ^b	1850 ± 1.18 ^b	2360 ± 1.10 ^a	1407 ± 2.66 ^b	1575 ± 1.05 ^a	2945 ± 1.88 ^a	1760 ± 1.25 ^b	2540 ± 2.72 ^a	2055 ± 3.55 ^b
Mean	4212 ± 4.73^a	3042 ± 5.03^b	3878 ± 4.62^a	2937 ± 2.80^b	2162 ± 3.34^b	2380 ± 3.14^a	1904 ± 3.43^b	2015 ± 3.13^a	3053 ± 6.23^a	2302 ± 4.25^b	2934 ± 3.72^a	2294 ± 3.35^b
ANOVA												
FS	***		***		***		***		***		***	
Variety	***		***		***		***		***		***	
FS * Variety	***		***		***		***		***		***	**

Values are expressed as mean ± standard deviation (n = 3). Different letters within the same row indicate statistically significant differences ($p \leq 0.05$, Tukey's test). ** indicates a significant difference at the 1% probability level ($p < 0.01$), whereas *** indicates a significant difference at the 0.1% probability level ($p < 0.001$). FS: farming system; CF: conventional farming; OF: organic farming.

In 2023, low rainfall combined with high temperatures resulted in a general reduction in grain yield. At Beja, mean yield reached $2380 \text{ kg}\cdot\text{ha}^{-1}$ under organic farming compared with $2162 \text{ kg}\cdot\text{ha}^{-1}$ under conventional farming, while at Bousselem it amounted to $2015 \text{ kg}\cdot\text{ha}^{-1}$ under organic farming and $1904 \text{ kg}\cdot\text{ha}^{-1}$ under conventional farming, respectively. Despite these unfavorable conditions, most varieties exhibited comparable or even higher performance under organic farming than under conventional farming at both sites. INRAT 100 stood out with high organic yields at Beja ($2830 \text{ kg}\cdot\text{ha}^{-1}$) and Bousselem ($2353 \text{ kg}\cdot\text{ha}^{-1}$), consistently exceeding those obtained under conventional farming. Similarly, Monastir displayed high organic yields at both sites ($2888 \text{ kg}\cdot\text{ha}^{-1}$ at Beja and $2340 \text{ kg}\cdot\text{ha}^{-1}$ at Bousselem). Biskri also showed good adaptation to organic farming, with yields of $2675 \text{ kg}\cdot\text{ha}^{-1}$ at Beja and $2370 \text{ kg}\cdot\text{ha}^{-1}$ at Bousselem, confirming its relative performance under water stress conditions (Table 3).

In 2024, mean grain yields reached $2294 \text{ kg}\cdot\text{ha}^{-1}$ under organic farming and $2934 \text{ kg}\cdot\text{ha}^{-1}$ under conventional farming. At Beja, the varieties Biskri (landrace) and Monastir (improved) exhibited superior performance under organic farming compared with the other genotypes, whereas for most varieties, yields under conventional farming remained higher. A site effect was also evident, with Beja generally exhibiting higher yields than Bousselem, depending on the experimental year and farming system (Table 3).

Across the three-year period, organic farming consistently resulted in reduced grain yield, mainly associated with a decrease in the number of grains per square meter and lower mean grain weight. Nevertheless, certain varieties, such as Dhahbi, Monastir, and Biskri, demonstrated better performance and adaptation under organic farming conditions.

3.3 Stability Analysis

Mean yields (Yld) ranged from 2195 to $2889 \text{ kg}\cdot\text{ha}^{-1}$, with the highest values observed for Dhahbi, Khiar, Biskri, and INRAT 100, whereas Jenah Khotifa, Saragolla, and Mahmoudi exhibited the lowest yields.

The regression coefficients (b_i) indicated contrasting varietal responses. Values close to unity were recorded for Monastir ($b_i = 1.00$), Karim ($b_i = 1.00$), Salim ($b_i = 0.91$), and INRAT 100 ($b_i = 0.99$), reflecting average responsiveness to environmental variation. In contrast, Chili ($b_i = 1.25$), Razzak ($b_i = 1.13$), and Saragolla ($b_i = 0.68$) showed differentiated responses, indicating either greater sensitivity to favorable environments or better adaptation to less favorable conditions, depending on the genotype (Table 4).

Stability parameters, including deviation from regression (s^2d_i), coefficient of variation (CV_i), and Wricke's ecovalence (W_i^2), revealed substantial inter-varietal heterogeneity. The lowest s^2d_i values were recorded for Salim ($s^2d_i = 0.00$), Monastir ($s^2d_i = 0.04$), and Dhahbi ($s^2d_i = 0.01$), whereas the highest values were observed for Saragolla ($s^2d_i = 1.88$) and Chili ($s^2d_i = 1.28$). Similarly, Wricke's ecovalence (W_i^2) varied widely, ranging from 0.30 for Salim to 45.67 for Monastir (Table 4).

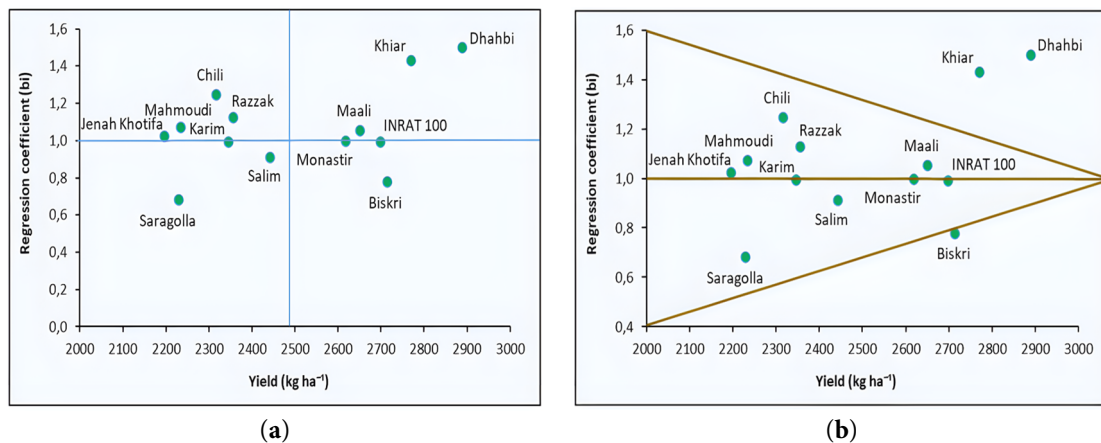
The synthetic indices confirmed these patterns. Dhahbi, Khiar, and INRAT 100 combined high yield performance with favorable rankings, exhibiting P_i values of 24.33, 4.25, and 7.71, respectively, GAI values of 27.33, 26.35, and 25.84, respectively, and mean grain yields ranging from 2698 to $2889 \text{ kg}\cdot\text{ha}^{-1}$. Biskri, despite its high mean yield ($2713 \text{ kg}\cdot\text{ha}^{-1}$) and high GAI (25.33), also exhibited a favorable P_i value (7.96), confirming its good overall performance. Conversely, Jenah Khotifa (Yld = $2195 \text{ kg}\cdot\text{ha}^{-1}$), Mahmoudi (Yld = $2233 \text{ kg}\cdot\text{ha}^{-1}$), and Saragolla (Yld = $2229 \text{ kg}\cdot\text{ha}^{-1}$) showed unfavorable rankings across most stability indices, with P_i values ranging from 32.40 to 38.36 and GAI values from 21.01 to 21.38, reflecting lower mean yield and reduced adaptability to the experimental conditions (Table 4).

Table 4: Stability parameters of grain yield in thirteen durum wheat genotypes under organic farming conditions across three experimental years (2022–2024).

Var	R	Yld	b_i	R	$s^2 d_i$	R	CVi	R	W_i^2	R	Pi	R	GAI	R	MR
Dhahbi	1	2889	1.50	13	0.01	2	26.58	13	22.91	12	24.33	7	27.33	1	8
Khlar	2	2770	1.43	12	0.56	8	22.76	11	10.80	9	4.25	2	26.35	2	6
Biskri	3	2713	0.78	5	0.05	4	12.45	2	2.15	3	7.96	4	25.33	6	1
INRAT 100	4	2698	0.99	3	1.16	11	17.48	4	8.09	7	7.71	3	25.84	4	2
Maali	5	2650	1.05	8	0.56	7	17.88	6	4.04	5	8.44	5	25.39	5	5
Monastir	6	2618	1	1	0.04	3	2.31	1	45.67	13	1.47	1	26.12	3	3
Salim	7	2442	0.91	4	0	1	16.05	3	0.30	1	19	6	23.46	7	4
Razzak	8	2355	1.13	10	1.09	10	22.17	10	8.20	8	24.86	8	22.44	9	11
Karim	9	2345	1	2	0.59	9	19.24	7	4.15	6	25.52	9	22.45	8	7
Chili	10	2316	1.25	11	1.28	12	24.86	12	11.19	10	26.22	10	22.01	10	13
Mahmoudi	11	2233	1.07	9	0.45	6	21.41	9	3.33	4	32.40	11	21.34	12	9
Saragolla	12	2229	0.68	6	1.88	13	17.48	5	16.82	11	38.36	13	21.38	11	12
Jenah Khotifa	13	2195	1.02	7	0.18	5	20.35	8	1.29	2	35.56	12	21.01	13	10

Grain yield (Yld, $\text{kg}\cdot\text{ha}^{-1}$) and stability parameters included coefficient of variation (CVi), linear regression coefficient (b_i), deviation from regression ($s^2 d_i$), Wricke's ecovalence (W_i^2), Shukla's stability variance (σ^2_i), Plaisted and Peterson's stability parameter (θ_i), Lin and Binns' superiority index (Pi), geometric adaptability index (GAI), and their corresponding ranks (R) and mean ranks (MR).

The clustering of genotypes illustrated in Fig. 3 confirms the patterns observed in the stability analyses. The varieties Monastir and INRAT100 under the organic farming system stand out as the most stable and high-performing genotypes, with elevated grain yields of 2618 and 2698 $\text{kg}\cdot\text{ha}^{-1}$, respectively, and regression coefficients close to unity ($b_i = 1.00$ and $b_i = 0.99$), indicating moderate sensitivity to environmental variation and broad adaptation across the tested conditions.

**Figure 3:** Stability analysis of grain yield (GY): (a) relationship between the adaptability of organic durum wheat genotypes and their average grain yield across two environments over three years of experimentation; (b) relationship between the regression coefficient and the average grain yield of 13 durum wheat genotypes grown under organic conditions across two environments over three years of trials, according to Finlay and Wilkinson (1963).

In contrast, the varieties Khlar (2770 $\text{kg}\cdot\text{ha}^{-1}$, $b_i = 1.43$) and Dhahbi (2889 $\text{kg}\cdot\text{ha}^{-1}$, $b_i = 1.50$) exhibited pronounced instability despite their high yield levels, as their regression coefficients greater than 1 reflect increased sensitivity to environmental fluctuations. Similarly, Chili ($b_i = 1.25$) and Razzak ($b_i = 1.13$) were also classified as unstable genotypes.

Among the lower-yielding varieties, Saragolla (2229 $\text{kg}\cdot\text{ha}^{-1}$, $b_i = 0.68$) showed notable stability, reflecting low responsiveness to environmental changes and good adaptation to unfavorable environments.

Likewise, Biskri, combining a high mean yield ($2713 \text{ kg}\cdot\text{ha}^{-1}$) with a regression coefficient below unity ($b_i = 0.78$), was classified as a stable genotype, particularly adapted to less favorable conditions.

The varieties Jenah Khotifa ($b_i = 1.02$), Mahmoudi ($b_i = 1.07$), and Salim ($b_i = 0.91$) exhibited relative stability despite yields below the overall mean, whereas Maali showed a favorable compromise between yield ($2650 \text{ kg}\cdot\text{ha}^{-1}$) and stability ($b_i = 1.05$), indicating intermediate adaptability across environments.

Correlation matrix

The correlation matrix highlights the relationships among the different stability and performance indices of the genotypes (Table 5). A highly significant and strong positive correlation was observed between mean grain yield (Yield) and the geometric adaptability index (GAI) ($r = 1.00$), indicating that the most productive genotypes also exhibit superior adaptability to the experimental conditions. Similarly, the Lin and Binns superiority index (P_i) showed a strong and highly significant negative correlation with mean yield ($r = -0.95$), which is consistent with its conceptual definition, as lower P_i values indicate higher-performing and more stable genotypes.

The Wricke's ecovalence index (W_i^2) was very strongly and positively correlated with the other stability indices ($r = 1.00$), reflecting its consistent ability to quantify genotype variability in response to environmental conditions. The linear regression coefficient (b_i) exhibited a moderate positive correlation with the coefficient of variation (CVi) ($r = 0.59$), suggesting that genotypes showing greater sensitivity to environmental fluctuations also tend to display higher yield variability.

Finally, weak or non-significant correlations between certain stability indices and P_i or GAI (e.g., W_i^2 vs. P_i) indicate that these indices capture different and complementary aspects of yield performance and stability. This highlights the importance of using a combination of stability parameters to achieve a comprehensive evaluation of the overall performance and adaptability of durum wheat genotypes under contrasting farming systems.

Table 5: Pearson's correlation coefficient for all stability parameters studied over the years of trials under organic conditions.

Variables	Yield	b_i	s^2d_i	CVi	W_i^2	P_i	GAI
Yield	1						
b_i	0.43	1					
s^2d_i	-0.39	-0.21	1				
CVi	-0.11	0.59*	0.27	1			
W_i^2	0.30	0.17	-0.06	-0.48	1		
P_i	-0.95***	-0.47	0.36	-0.09	-0.01	1	
GAI	1.00***	0.38	-0.41	-0.18	0.32	-0.94***	1

*, ***: The correlation is significant at the 5% ($p < 0.05$) and 0.1% ($p < 0.001$) probability levels, respectively.

3.4 Grain Quality Traits

Grain moisture content, considered a key parameter of technological quality, showed comparable mean values between the two farming systems, reaching 10.39% under conventional farming and 10.21% under organic farming (Table 6). However, analysis of variance (Table 6; Table S4) revealed a highly significant effect of the farming system on this trait ($p < 0.001$). At the varietal level, marked differences were observed, particularly for the Biskri and Mahmoudi varieties, which exhibited the largest contrasts between farming systems, with moisture contents decreasing from 12.37% and 10.50% under conventional farming to 9.85% and 9.89% under organic farming, respectively. Overall, nine out of the thirteen varieties displayed lower grain moisture under organic farming. Furthermore, Table 6 highlighted a highly significant varietal effect

on grain moisture content ($p < 0.001$), with values under organic farming ranging from 9.79% for Khair to 11.34% for Karim, while under conventional farming they varied from 9.44% for Chili to 11.24% for Biskri.

In parallel, analysis of variance of grain test weight (TW) (Table 6) showed a highly significant difference between the two farming systems ($p < 0.001$), with mean values of $78.77 \text{ kg}\cdot\text{hL}^{-1}$ under conventional farming and $79.61 \text{ kg}\cdot\text{hL}^{-1}$ under organic farming, corresponding to a 1.07% increase in favor of organic farming (Table 6). All varieties grown under organic farming exhibited test weight values above the regulatory threshold of $76.5 \text{ kg}\cdot\text{hL}^{-1}$, whereas some varieties cultivated under conventional farming fell below this limit. Across all thirteen genotypes, mean test weight was consistently higher under organic farming, with the Biskri variety showing the most pronounced increase (+5.63%), rising from $78.10 \text{ kg}\cdot\text{hL}^{-1}$ under conventional farming to $82.50 \text{ kg}\cdot\text{hL}^{-1}$ under organic farming. Similarly, Mahmoudi and Monastir recorded high test weight values under organic farming, reaching 82.00 and $81.80 \text{ kg}\cdot\text{hL}^{-1}$, respectively.

Regarding grain vitreousness (VitA), analysis of variance revealed highly significant effects ($p < 0.001$) of the farming system, variety, and their interaction on this trait (Table 6). On average, vitreousness was higher under organic farming (44.20%) than under conventional farming (43.95%). Landraces (Chili, Biskri, Mahmoudi, and Jenah Khotifa) consistently exhibited markedly higher vitreousness levels than modern varieties under both farming systems, with values reaching or exceeding 50%. Several landraces, particularly Chili, showed an increase in vitreousness under organic farming, rising from 54.37% under conventional farming to 57.17% under organic farming, whereas modern varieties generally exhibited smaller variations or slight decreases in VitA (Table 6).

Grain protein content was significantly influenced by the farming system, variety, and their interaction ($p < 0.001$) (Table 6). On average, conventional farming resulted in significantly higher protein content (13.68% DM) compared with organic farming (13.40% DM), reflecting the direct effect of nitrogen fertilization strategies associated with each farming system. At the varietal level, highly significant differences were observed among the thirteen genotypes, with protein contents ranging from 12.22% to 15.50% DM depending on the farming system. The Karim and Razzak varieties showed the highest protein levels under conventional farming, whereas several local varieties, notably Mahmoudi, Biskri, Chili, and Jenah Khotifa, exhibited significantly higher protein contents under organic farming, with relative increases reaching +8.76% for Mahmoudi and +8.38% for Biskri (Table 6).

Consistently, analysis of variance indicated a highly significant effect ($p < 0.001$) of the farming system, variety, and their interaction on wet gluten content (Table 6). Values ranged from 32.00% to 34.97% under conventional farming and from 28.21% to 34.77% under organic farming, with respective means of 33.11% and 32.40%, placing all genotypes within a technologically satisfactory to good gluten category. Modern varieties generally exhibited higher wet gluten contents under conventional farming, whereas landraces showed significantly higher values under organic farming, particularly Mahmoudi (34.77%) and Chili (34.02%). Similarly, the gluten index was strongly affected by the farming system, variety, and their interaction ($p < 0.001$) (Table 6), with values ranging from 45.03% to 86.80% and an overall mean of 67.73%. The mean gluten index was higher under conventional farming (70.13%) than under organic farming (65.33%), indicating overall balanced gluten quality compatible with good technological performance.

In contrast, dry gluten content was not significantly affected by the farming system, whereas the effects of variety and the farming system $\times$ variety interaction were highly significant ($p < 0.001$) (Table 6). Under conventional farming, dry gluten ranged from 10.72% to 18.58% (mean 14.44%), while under organic farming it varied from 8.90% to 19.13% (mean 14.39%), with the highest values observed for Biskri, Jenah Khotifa, Razzak, and Dhahbi (Table 6).

Table 6: Technological grain quality traits of thirteen durum wheat varieties under conventional and organic farming systems.

Varieties	Farming System	Grain Moisture	Test Weight	Vitreousness	Protein Content	Wet Gluten	Dry Gluten	Gluten Index	Semolina Yield
Karim	Conventional	10.24 ± 0.00 ^b	79.37 ± 0.00 ^a	47.40 ± 0.00 ^a	15.50 ± 0.01 ^a	34.04 ± 0.03 ^a	14.83 ± 0.10 ^b	86.80 ± 2.79 ^a	74.79 ± 0.01 ^a
	Organic	11.34 ± 0.00 ^a	79.43 ± 0.01 ^a	44.65 ± 0.01 ^b	13.42 ± 0.02 ^b	30.86 ± 0.02 ^b	16.23 ± 0.32 ^a	66.00 ± 0.44 ^b	68.67 ± 0.01 ^b
Razzak	Conventional	9.82 ± 0.00 ^b	76.40 ± 0.00 ^b	39.88 ± 0.01 ^b	15.24 ± 0.04 ^a	33.16 ± 0.25 ^a	12.87 ± 0.06 ^b	84.90 ± 0.36 ^a	72.56 ± 0.00 ^a
	Organic	10.21 ± 0.00 ^a	77.13 ± 0.00 ^a	42.82 ± 0.00 ^a	13.20 ± 0.05 ^b	31.95 ± 0.17 ^b	18.50 ± 0.50 ^a	65.03 ± 0.64 ^b	71.66 ± 0.00 ^b
Khlar	Conventional	10.12 ± 0.00 ^a	79.23 ± 0.00 ^b	41.61 ± 0.00 ^a	12.47 ± 0.02 ^a	32.44 ± 0.23 ^a	10.72 ± 0.10 ^a	51.97 ± 1.85 ^a	73.26 ± 0.00 ^a
	Organic	9.79 ± 0.01 ^b	80.60 ± 0.00 ^a	38.89 ± 0.02 ^b	12.22 ± 0.07 ^b	29.30 ± 0.00 ^b	9.17 ± 0.06 ^b	45.03 ± 0.06 ^b	69.12 ± 0.02 ^b
Maali	Conventional	10.42 ± 0.00 ^a	77.17 ± 0.00 ^b	33.74 ± 0.00 ^b	12.66 ± 0.05 ^a	34.72 ± 0.20 ^a	14.50 ± 0.40 ^a	55.77 ± 0.86 ^a	74.37 ± 0.00 ^a
	Organic	10.22 ± 0.00 ^b	77.80 ± 0.00 ^a	36.52 ± 0.00 ^a	12.31 ± 0.01 ^b	33.63 ± 0.00 ^b	11.60 ± 0.13 ^b	50.07 ± 0.31 ^b	71.10 ± 0.00 ^b
Salim	Conventional	10.53 ± 0.01 ^a	79.37 ± 0.01 ^b	33.23 ± 0.02 ^a	13.31 ± 0.04 ^a	32.41 ± 0.10 ^a	14.27 ± 0.15 ^a	65.30 ± 0.90 ^a	71.45 ± 0.00 ^a
	Organic	10.24 ± 0.00 ^b	79.77 ± 0.00 ^a	30.70 ± 0.02 ^b	12.75 ± 0.07 ^b	28.21 ± 0.00 ^b	8.90 ± 0.10 ^b	56.13 ± 1.21 ^b	69.66 ± 0.01 ^b
INRAT 100	Conventional	10.77 ± 0.00 ^a	79.83 ± 0.00 ^b	39.52 ± 0.02 ^a	14.36 ± 0.05 ^a	33.82 ± 0.09 ^a	17.67 ± 0.25 ^a	68.63 ± 2.02 ^b	72.69 ± 0.02 ^a
	Organic	10.46 ± 0.00 ^b	80.47 ± 0.00 ^a	36.98 ± 0.00 ^b	14.38 ± 0.02 ^a	32.94 ± 0.23 ^b	13.10 ± 0.10 ^b	70.17 ± 1.00 ^a	66.92 ± 0.01 ^b
Dhahbi	Conventional	10.84 ± 0.00 ^a	81.33 ± 0.00 ^a	44.39 ± 0.00 ^a	14.75 ± 0.06 ^a	34.97 ± 0.17 ^a	18.58 ± 0.20 ^a	83.60 ± 1.31 ^a	75.08 ± 0.00 ^a
	Organic	9.96 ± 0.00 ^b	81.40 ± 0.00 ^a	41.64 ± 0.00 ^b	13.59 ± 0.00 ^b	33.44 ± 0.18 ^b	17.10 ± 0.36 ^b	66.83 ± 0.85 ^b	71.36 ± 0.00 ^b
Monastir	Conventional	10.51 ± 0.00 ^a	81.60 ± 0.00 ^b	37.54 ± 0.03 ^b	13.80 ± 0.03 ^a	33.14 ± 0.24 ^a	12.97 ± 0.12 ^a	68.60 ± 1.39 ^a	72.09 ± 0.02 ^a
	Organic	9.98 ± 0.00 ^b	81.80 ± 0.01 ^a	40.19 ± 0.01 ^a	12.82 ± 0.02 ^b	32.04 ± 0.22 ^b	10.83 ± 0.21 ^b	57.47 ± 0.84 ^b	69.68 ± 0.01 ^b
Saragolla	Conventional	10.24 ± 0.01 ^a	78.93 ± 0.00 ^a	45.03 ± 0.00 ^a	14.03 ± 0.03 ^a	33.46 ± 0.21 ^a	13.93 ± 0.49 ^a	70.80 ± 0.60 ^a	72.69 ± 0.03 ^a
	Organic	10.00 ± 0.00 ^b	79.47 ± 0.00 ^b	42.36 ± 0.00 ^b	14.02 ± 0.02 ^a	32.34 ± 0.21 ^b	11.93 ± 0.67 ^b	69.93 ± 1.39 ^b	70.67 ± 0.00 ^b
Chili	Conventional	9.44 ± 0.00 ^b	75.30 ± 0.00 ^b	54.37 ± 0.00 ^b	12.40 ± 0.00 ^b	32.04 ± 0.00 ^b	13.77 ± 0.25 ^b	72.10 ± 0.79 ^b	67.12 ± 0.01 ^b
	Organic	10.05 ± 0.00 ^a	76.40 ± 0.00 ^a	57.17 ± 0.00 ^a	13.38 ± 0.03 ^a	34.02 ± 0.01 ^a	16.03 ± 0.32 ^a	83.50 ± 0.50 ^a	73.28 ± 0.00 ^a
Biskri	Conventional	11.24 ± 0.00 ^a	78.10 ± 0.00 ^b	53.06 ± 0.00 ^b	13.00 ± 0.02 ^b	32.15 ± 0.04 ^b	13.73 ± 0.31 ^b	69.37 ± 1.15 ^b	66.69 ± 0.00 ^b
	Organic	9.85 ± 0.00 ^b	82.50 ± 0.00 ^a	55.82 ± 0.00 ^a	14.09 ± 0.04 ^a	33.86 ± 0.10 ^a	19.13 ± 0.72 ^a	71.50 ± 0.20 ^a	72.69 ± 0.01 ^a
Mahmoudi	Conventional	11.05 ± 0.00 ^a	80.13 ± 0.00 ^b	49.95 ± 0.00 ^b	13.24 ± 0.02 ^b	32.03 ± 0.12 ^b	16.30 ± 0.26 ^a	68.70 ± 0.72 ^b	65.12 ± 0.00 ^b
	Organic	9.89 ± 0.00 ^b	82.00 ± 0.00 ^a	52.59 ± 0.00 ^a	14.40 ± 0.04 ^a	34.77 ± 0.09 ^a	15.87 ± 0.42 ^b	71.53 ± 1.11 ^a	74.65 ± 0.00 ^a
Jenah Khotifa	Conventional	9.89 ± 0.00 ^b	77.20 ± 0.00 ^a	51.56 ± 0.01 ^b	13.04 ± 0.03 ^b	32.00 ± 0.08 ^b	13.60 ± 0.26 ^b	65.17 ± 0.59 ^b	65.69 ± 0.01 ^b
	Organic	10.79 ± 0.00 ^a	76.17 ± 0.00 ^b	54.30 ± 0.00 ^a	13.68 ± 0.01 ^a	33.83 ± 0.03 ^a	18.67 ± 0.15 ^a	76.07 ± 0.87 ^a	72.67 ± 0.00 ^a
Mean	Conventional	10.39 ± 0.50^a	78.77 ± 1.81^b	43.95 ± 6.89^a	13.68 ± 1.01^a	33.11 ± 1.02^a	14.44 ± 2.03^a	70.13 ± 10.09^a	71.05 ± 3.48^a
	Organic	10.21 ± 0.42^b	79.61 ± 2.09^a	44.20 ± 8.07^a	13.40 ± 0.71^a	32.40 ± 1.89^b	14.39 ± 3.56^a	65.33 ± 10.39^b	70.93 ± 2.06^a
ANOVA									
Farming System		***	***	***	***	***	NS	***	***
Variety		***	***	***	***	***	***	***	***
FS * Variety		***	***	***	***	***	***	***	***

Technological quality traits included grain moisture content (%), test weight (kg·hL⁻¹), grain vitreousness (%), protein content (% DM), wet gluten content (%), dry gluten content (%), gluten index (-), and semolina yield (%). Values are expressed as mean ± standard deviation (n = 3). Different letters within the same row indicate statistically significant differences ($p < 0.05$, Tukey's test). *** indicates a significant difference at the 0.1% probability level ($p < 0.001$), whereas NS indicates a non-significant difference ($p > 0.05$).

Finally, mean semolina yield showed very similar values between the two farming systems, ranging from 65.12% to 75.08% under conventional farming and from 66.92% to 74.65% under organic farming, with respective overall means of 71.05% and 70.93%. Statistical analysis revealed a highly significant effect of the farming system and variety ($p < 0.001$), reflecting contrasting responses among genotypes. Some modern varieties exhibited marked inter-system stability, whereas Tunisian landraces such as Mahmoudi, Jenah Khotifa, Biskri, and Chili displayed reversed performance patterns, characterized by lower semolina yields under conventional farming but markedly improved yields under organic farming, highlighting a strong variety $\times$ farming system interaction (Table 6).

3.5 Relationships between Grain Yield, Yield Components, and Grain Quality Parameters

The correlation matrix highlights significant relationships among yield components, semolina yield, and technological quality parameters in durum wheat (Table 7). A significant negative correlation was observed between the number of spikes per m^2 and the number of grains per spike ($r = -0.552$), reflecting a compensatory effect between these two yield components. Grain yield was strongly and positively correlated with the number of grains per spike ($r = 0.716^{**}$), whereas it was negatively correlated with the number of spikes per m^2 ($r = -0.582^*$), indicating that yield formation was more closely associated with spike productivity than with spike density. In contrast, no significant correlations were detected between grain yield and thousand-grain weight (TGW) or grain number per m^2 . Furthermore, semolina yield was positively correlated with the number of spikes per m^2 ($r = 0.735^{**}$), while no significant relationships were observed with TGW, grains per spike, or grains per m^2 , suggesting a partial decoupling between agronomic yield and processing yield. Regarding technological quality traits, positive and significant to highly significant correlations were observed among the different quality parameters. Grain vitreousness was positively correlated with wet gluten content ($r = 0.677^*$), gluten index ($r = 0.757^{**}$), dry gluten content ($r = 0.750^{**}$), and semolina yield ($r = 0.742^{**}$), highlighting the importance of grain endosperm structure in determining technological quality. Similarly, grain protein content was positively correlated with wet gluten content ($r = 0.578^*$) and gluten index ($r = 0.778^*$). Finally, gluten-related parameters (wet gluten, dry gluten, and gluten index) exhibited significant positive correlations with one another, with coefficients ranging from 0.633 to 0.705, indicating strong functional coherence among these indicators of technological quality (Table 7).

3.6 Principal Component Analysis (PCA)

The principal component analysis (PCA) performed on the full set of agronomic and technological traits revealed a clear structuring of variability, with the first two axes explaining 61.14% of the total inertia (PC1 = 40.30%; PC2 = 20.84%), indicating a satisfactory representation of the original information (Fig. 4).

PC1: Technological quality and semolina valorization gradient

The first principal component (PC1) was mainly structured by grain technological quality traits. It was mainly associated with vitreousness, wet gluten, dry gluten, gluten index, protein content, and semolina yield. The small angular distances and relatively long vectors associated with these variables indicate their major contribution to this axis and reflect a strong functional coherence among these quality criteria.

This grouping confirms the existence of a technological gradient, distinguishing genotypes characterized by a high aptitude for semolina processing associated with a dense and vitreous endosperm structure and a well-developed gluten network to genotypes exhibiting lower values for these parameters. This pattern is fully consistent with the strong positive correlations observed between vitreousness, gluten-related traits, and semolina yield, highlighting the central role of internal grain structure in the technological valorization of durum wheat.

Table 7: Pearson correlation matrix between yield components and grain quality traits of durum wheat, including spike number (spikes m^{-2}), number of grains per spike (grains spike^{-1}), number of grains per square meter (grains m^{-2}), thousand-grain weight (TKW, g), grain yield (GY), grain moisture content (%), test weight (kg hL^{-1}), vitreousness (%), grain protein content (%), wet gluten (%), dry gluten (%), gluten index (–), and semolina yield (%).

Variables	Spikes m^{-2}	Grains spike^{-1}	Grains m^{-2}	TKW	Grain Yield	Moisture Content	Test Weight	Vitreousness	Protein	Wet Gluten	Dry Gluten	Gluten Index	Semolina Yield
Spikes m^{-2}	1												
Grains spike^{-1}	–0.552	1											
Grains m^{-2}	0.460	0.485	1										
TKW	–0.180	0.013	–0.162	1									
Grain yield	–0.582*	0.716**	0.162	0.056	1								
Moisture content	–0.209	–0.142	–0.376	–0.021	–0.365	1							
Test weight	0.038	0.347	0.440	–0.096	0.519	–0.414	1						
Vitreousness	0.671*	–0.309	0.377	0.316	–0.397	–0.014	–0.150	1					
Protein	0.427	–0.199	0.254	0.350	–0.287	0.078	0.241	0.503	1				
Wet gluten	0.338	0.187	0.549	0.386	–0.124	–0.125	–0.065	0.677*	0.578*	1			
Dry gluten	0.323	–0.223	0.109	0.618*	–0.228	0.237	–0.191	0.750**	0.559*	0.635*	1		
Gluten index	0.577*	–0.483	0.089	0.384	–0.496	0.177	–0.244	0.757**	0.778**	0.633*	0.705**	1	
Semolina yield	0.735**	–0.278	0.468	0.247	–0.405	–0.340	–0.158	0.742**	0.253	0.623*	0.555*	0.477	1

* and ** indicate significant correlations at the 5% ($p < 0.05$) and 1% ($p < 0.001$) probability levels, respectively.

Interestingly, the number of spikes per m^2 was also positively associated with PC1 and was positioned in the same general direction as the technological quality traits, particularly vitreousness and semolina yield. This pattern is consistent with the positive correlations observed between spike number and vitreousness ($r = 0.671^*$), semolina yield ($r = 0.735^*$), gluten index ($r = 0.577^*$), protein content ($r = 0.427$), wet gluten ($r = 0.338$), and dry gluten ($r = 0.323$) (Table 7). Therefore, the PCA does not support a trade-off between spike density and technological quality; rather, it indicates a positive association between spike density and several grain quality attributes under the conditions of this study.

PC2: Yield potential versus grain water status

The second principal component (PC2) was primarily structured by yield-related variables, with positive contributions from the number of grains per spike, grain yield, and test weight, whereas grain moisture content was negatively projected on this axis. This configuration describes a gradient contrasting genotypes associated with higher grain productivity and test weight with those characterized by higher grain moisture content at harvest.

The joint projection of grain yield and number of grains per spike within the same quadrant is consistent with their strong positive correlation ($r = 0.716^{**}$), confirming the close association between these two variables under the conditions of the present study. Conversely, the relatively weak and non-significant correlations of grain yield with TKW and grain number per m^2 indicate that these traits were less closely associated with grain yield. The opposite orientation of the grain moisture vector suggests an inverse association between grain moisture and the yield-related variables represented along PC2.

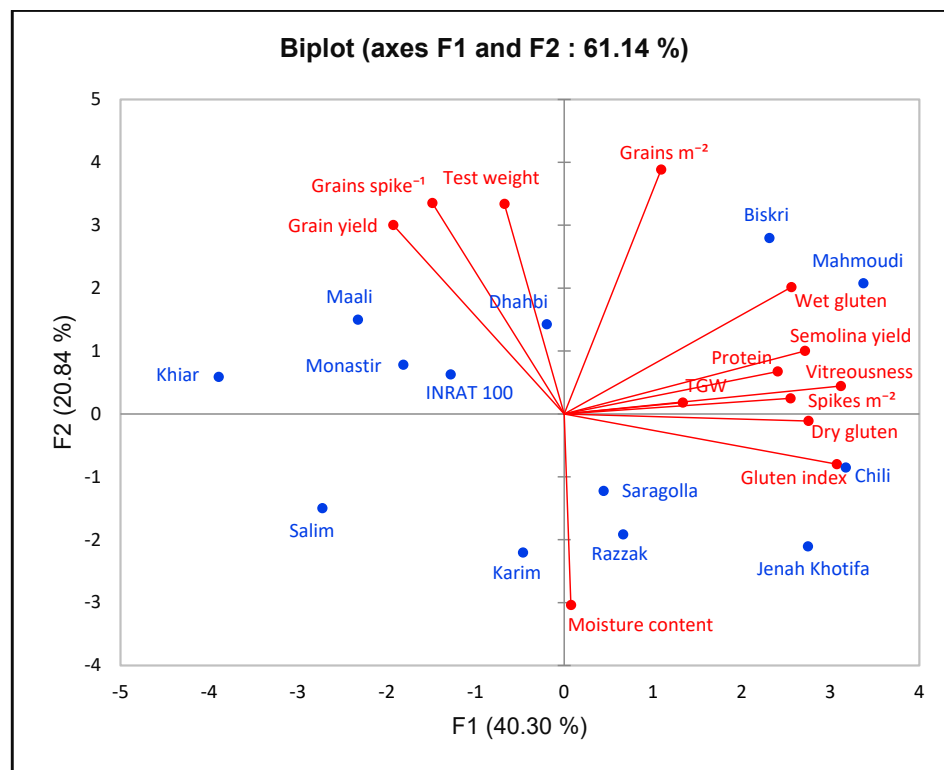


Figure 4: Biplot of principal component analysis illustrating the associations between yield performance, yield components, and grain quality traits in durum wheat under organic farming conditions.

4 Discussion

4.1 Agronomic Traits and Yield Component Responses to Farming System

The transition from conventional farming to organic farming frequently results in a reduction of the main yield components of durum wheat, particularly the number of grains per spike and the mean grain weight, whereas spike density may remain comparable depending on crop management [50,51]. This response can be partly attributed to the increased sensitivity of early germination and establishment stages to water and thermal constraints, leading to less favorable stand establishment of young plants [52].

The reduction in plant density observed under organic farming can be ascribed to the higher sensitivity of establishment phases to environmental stresses and to a lower synchronization between nutrient availability and crop demand. It has been widely demonstrated that, in organic farming systems, resource limitations and climatic variability exert stronger effects on early crop establishment, resulting in lower final plant density and a canopy structure less conducive to yield formation [50]. This situation directly affects stand organization and subsequently conditions the establishment of spike number per unit area.

The decrease in spike number per m² and in the number of grains per spike under organic farming reflects a reduction in fertile tillering capacity and floret fertility, two processes that are highly dependent on water and nitrogen availability during pre-anthesis stages [53]. The relative stability of aboveground biomass combined with the reduction of yield components under organic farming further supports the notion that differences in traits such as grain number per spike and grain weight are the primary drivers of yield variation between farming systems. Comparative studies have shown that, even when total yield levels are similar in some cases, numerical yield components such as grains per spike and grain weight are often lower under organic farming [51].

The lower mean grain weight observed under organic farming may be associated with the effects of thermal stress during post-anthesis grain filling, which reduces both the duration and efficiency of grain filling and ultimately limits final grain weight. This physiological trade-off between grain number and grain weight highlights the critical role of grain filling processes and post-anthesis assimilate remobilization in determining yield under conditions of thermal stress [54].

Overall, performance under organic farming relies on the stability of spike fertility, the maintenance of fertile tillers, the efficiency of assimilate remobilization, and resilience to pre- and post-anthesis water and thermal stresses [51,53]. These findings underscore the importance of targeted varietal selection focused on the physiological determinants of yield components and on the adaptive plasticity of genotypes in constrained Mediterranean environments.

4.2 Agronomic Performance

The analysis of durum wheat yields over three experimental years (2022–2024) highlights the combined importance of climatic factors, farming systems, and genotype × environment interactions in determining productivity in Mediterranean environments. In such contexts, the amount and temporal distribution of rainfall, together with the occurrence of thermal stress events, exert a major influence on cereal yield variability. This observation is consistent with the findings of Devkota et al. [55], who demonstrated that rainfall variability explains a substantial proportion of durum wheat yield variance under rainfed Mediterranean conditions. Grain yield under organic farming was consistently lower than under conventional farming, with the magnitude of the yield gap depending on environmental conditions, particularly temperature and precipitation, which directly affect water availability as well as crop growth and resource-use efficiency. Beyond its fundamental roles in photosynthesis, nutrient transport, and cell division, water represents a

critical environmental factor limiting crop growth and productivity [56]. Unexpected fluctuations in rainfall patterns and increasing temperatures, driven by climate change, are likely to increase the frequency of drought episodes in many regions [57]. Beyond their direct effects on yield and grain quality, environmental factors, particularly temperature, can also influence plant morphological and reproductive development. Previous studies have shown that thermal variation may modify reproductive traits, including floral development and the formation of reproductive organs, thereby affecting yield formation processes. In durum wheat, similar environmental effects may contribute to variations in plant establishment, tillering capacity, spike fertility, and grain number, which are key components determining final yield.

Several studies have shown that post-anthesis heat stress affects both yield and grain composition in wheat. Dias and Lidon [58] reported that exposure of durum and bread wheat genotypes to high temperatures after anthesis shortens the grain-filling duration and significantly reduces grain weight, leading to a marked yield decline under thermal stress. Similarly, Cosentino et al. [59] demonstrated a negative relationship between high post-anthesis temperatures and durum wheat yield, while also showing that thermal stress episodes alter grain composition through a relative increase in protein content associated with the shortening of the grain-filling period.

The lower average yields observed under organic farming, compared with conventional farming, can be explained by differences in resource availability and use efficiency, particularly for water and nutrients, between the two farming systems. This trend is consistent with the conclusions of Scandurra et al. [60], who showed that under water-limited Mediterranean conditions, low-input systems may be disadvantaged in terms of yield because biologically mediated nutrient release processes are less immediate than those operating in conventional farming. However, a regular and sufficient rainfall distribution contributes to improved wheat yields under rainfed conditions, especially in regions characterized by high climatic variability [61]. Moreover, water plays a crucial role in numerous metabolic processes, participating in biochemical reactions and in the transport of synthesized compounds, while also contributing to plant protection against thermal overheating [62].

During the second drought year (2023), characterized by very low rainfall combined with high evaporative demand, organic farming improved and optimized productivity compared with conventional farming for ten and eleven out of the thirteen tested varieties at the Beja and Bousselem sites, respectively.

The relatively higher performance of organically managed varieties under these severe drought conditions may be associated with differences in nutrient dynamics, crop growth regulation, and water use strategies between farming systems.

In Mediterranean rainfed environments, excessive nutrient availability under conventional management can promote vigorous vegetative development, increasing canopy demand for water and potentially accelerating soil moisture depletion during periods of prolonged drought. Conversely, organic systems generally rely on gradual nutrient mineralization processes, which may result in a more balanced vegetative development and improved synchronization between crop demand and resource availability. Furthermore, repeated organic inputs contribute to the improvement of soil physical properties, including soil aggregation and water retention capacity, which may enhance crop resilience under water-limited conditions.

The presence of amino acids in organic fertilizers may contribute to plant physiological regulation under environmental constraints; however, their contribution to drought adaptation depends on the plant metabolic response and the interaction with environmental conditions. Among stress-responsive compounds, proline accumulation has been widely reported as a physiological mechanism involved in osmotic adjustment and cellular protection under drought stress [63]. Proline may also participate in the regulation of carbon and nitrogen metabolism during stress conditions [64]. Nevertheless, the expression of

such physiological responses depends on genotype characteristics and stress intensity, and their contribution to yield performance requires further physiological investigation.

The superior performance of varieties such as INRAT100, Monastir, Maali, Khiar, and Biskri under organic farming in 2023 therefore suggests a greater adaptation of these genotypes to low-input conditions and their ability to maintain yield production under combined water and thermal constraints.

4.3 Yield Stability and Adaptability

The stability analysis showed that the cultivars Monastir and INRAT100, characterized by high grain yields and regression coefficients close to unity ($b_i \approx 1$), are well adapted to most of the tested environments, confirming their genetic plasticity and robustness to climatic variability. These findings are consistent with those reported by Bouatrous et al. [65], who demonstrated that certain durum wheat cultivars exhibit high yield stability under sub-humid Mediterranean rainfed conditions due to an intermediate adaptability to fluctuating environments.

Based on the general stability model proposed by Finlay and Wilkinson [35], similar trends were confirmed: Monastir and INRAT100 remained the most stable and broadly adapted cultivars across environments, whereas Dhahbi and Khiar were unstable but highly productive under favorable conditions. The yield stability observed in INRAT100 may be partly attributed to its genetic background, as this cultivar originates from crosses involving old and local parental lines that have developed strong adaptation to Tunisian environmental conditions through long-term evolutionary processes [66]. Likewise, Monastir exhibited wide stability, effectively exploiting favorable years while maintaining a minimum yield under dry conditions; its good tolerance to water stress has also been reported by Ayed et al. [67].

In contrast, Dhahbi and Khiar, despite their high yield potential, displayed regression coefficients greater than unity ($b_i > 1$), indicating increased sensitivity to favorable environments. This response, whereby high-yielding genotypes become unstable under less favorable conditions, has also been reported in recent studies on durum wheat performance and stability in hot and stress-prone environments [68].

Moreover, some cultivars with moderate or low mean yield, such as Saragolla and Biskri, showed remarkable stability ($b_i < 1$), indicating better adaptation to stressful environments. These observations support the concept that genotypes with $b_i < 1$ are generally more resilient to adverse climatic fluctuations [58].

In addition, the synthetic indices P_i and GAI enabled the identification of genotypes combining high yield with stability, thus providing priority candidates for breeding programs targeting variable Mediterranean environments. Our results further confirm that interannual yield variability and genotype $\times$ environment ($G \times E$) interactions play a central role in determining durum wheat performance, emphasizing that the differences observed among genotypes over the three experimental years reflect these interactions in addition to the direct effects of genotype and environment [69].

Overall, our findings demonstrate that certain cultivars, such as Monastir and INRAT100, successfully combine high yield and stability under organic farming, whereas other genotypes exhibit greater sensitivity to environmental variability, highlighting the importance of targeted varietal selection for different farming systems [70]. The integration of stability and adaptability indicators into breeding strategies is therefore essential to reconcile high productivity with yield stability, which represents a critical challenge for both organic farming and conventional farming under ongoing climate change [59].

4.4 Grain Quality Characteristics

All measured grain moisture values remained below the critical threshold associated with grain deterioration, in agreement with Ziegler et al. [71]. The relatively low moisture content observed in all

genotypes indicates good storage suitability and confirms the importance of moisture control for maintaining technological quality and limiting biochemical and microbial degradation during storage [72]. Test weight represents an important indicator of the physical and milling quality of durum wheat, integrating grain filling status, kernel structure, and maturation conditions [73]. The differences observed between farming systems highlight the combined effects of genotype and agronomic management on grain density. The higher test weight values under organic farming suggest improved grain filling and endosperm organization in some genotypes, particularly Biskri, Mahmoudi, and Monastir, indicating their potential adaptation to low-input conditions. As reported by Dimitrios [74], test weight is also influenced by grain moisture, environmental conditions during grain filling, and nitrogen availability. Therefore, the observed variability confirms the major role of genotype $\times$ environment interactions in determining grain physical quality [75].

The highly significant effects of farming system, variety, and their interaction on grain vitreousness confirm the importance of genetic and environmental factors in the expression of this trait. The slight increase in vitreousness under organic farming, particularly among landraces, suggests their capacity to maintain endosperm compactness under reduced nutrient availability, as reported by Sieber et al. [76]. The superior vitreousness of traditional genotypes agrees with previous studies showing that landraces retain valuable diversity for technological quality improvement aligns with the results of El-Khayat et al. [77]. This response may be related to differences in protein–starch organization within the endosperm and greater phenotypic plasticity of local varieties under low-input conditions [78–81].

Protein content was slightly higher under conventional farming than under organic farming (13.68 vs. 13.40% DM), which is consistent with previous studies attributing this difference to the faster availability of mineral nitrogen in conventional systems [82,83]. Similar trends have been reported in Tunisia by Ayadi et al. [84], confirming the importance of nitrogen management in durum wheat quality. However, the higher protein content observed in several local varieties (Mahmoudi, Biskri, Chili, and Jenah Khotifa) under organic farming highlights a genotype-dependent response and suggests a better capacity of these genotypes to utilize and remobilize organic nitrogen resources, as also demonstrated by Melki et al. [85] and Benzarti [86]. These results confirm that grain protein content is a trait with moderate to low heritability, strongly influenced by environmental conditions and management practices [82,83]. Wet gluten content followed a similar pattern, with significant effects of genotype and farming system. Modern varieties generally expressed higher gluten potential under conventional farming, whereas several landraces maintained or improved gluten accumulation under organic conditions, particularly Mahmoudi and Chili. This suggests a better adaptation of some local genotypes to limited nitrogen availability through efficient nitrogen acquisition and remobilization. Such characteristics make these genotypes valuable resources for breeding programs targeting organic farming systems, in agreement with the observations of Takač et al. [87], who emphasized the central role of nitrogen availability in the synthesis of storage proteins. Interestingly, organic farming was associated with a markedly greater inter-varietal variability in wet gluten content than conventional farming, indicating contrasting genotypic responses to reduced nitrogen availability. In contrast, landraces showed better performance under organic farming, suggesting superior adaptation to low-input production systems through a more efficient acquisition, remobilization, and utilization of available nitrogen during grain development. Among these, Mahmoudi and Chili maintained particularly high wet gluten contents under organic management, highlighting their potential as promising genetic resources for breeding and cultivar selection in organic farming systems. This adaptive ability explains the high values observed in Chili, Biskri, and Mahmoudi and supports their valorization in organic farming systems. These results further suggest that the capacity to maintain gluten accumulation under limited

nitrogen availability is strongly genotype-dependent and represents an important trait for improving grain technological quality in low-input agricultural systems.

The observed gluten index values generally indicate a well-balanced gluten quality, which is consistent with the results reported by Mitura et al. [88], who observed moderate differences between farming systems without major deterioration of gluten quality. Since the gluten index is known to be sensitive to climatic conditions during grain filling, Garrido-Lestache et al. [89] demonstrated that high temperatures during this phase favor an improvement in gluten index, which is consistent with the conditions recorded during the 2024 growing season. Moreover, the positive effect of late nitrogen fertilization on gluten rheological quality reported by Landolfi et al. [90] may explain the high values observed under conventional farming. The performances recorded for Chili, Biskri, and Karim also confirm observations made on Tunisian varieties by Daaloul Bouacha and Rezgui [91], highlighting a technologically balanced and stable gluten.

Furthermore, the predominance of the varietal factor over dry gluten content confirms the tight genetic control of this protein fraction. The observed values largely meet technological requirements, considering that a dry gluten content above 12% is generally regarded as satisfactory for bread-making applications [92]. The high values observed in several varieties under organic farming suggest that, despite lower nitrogen availability, some genotypes compensate through a more efficient allocation of nitrogen toward gluten structural proteins, in agreement with the findings of Guo et al. [93], who highlighted the key role of the three-dimensional gluten network, formed through thiol–disulfide exchanges, in determining dough viscoelastic properties.

Finally, semolina yield results highlight the existence of two distinct genetic pools: modern varieties exhibiting attractive yield stability for the semolina industry under conventional farming, and landraces showing marked improvement and superior technological robustness under organic farming. This inversion of performance validates the hypothesis of specific adaptation of local genetic resources to low-input systems and underscores the importance of considering genotype $\times$ environment interactions in varietal selection and recommendation for diversified and sustainable cereal production systems [70]. These observations further confirm the genetic plasticity of landraces and their potential for more sustainable farming systems, while remaining within the typical semolina yield range reported for durum wheat (60–75%), as documented in recent literature [94].

4.5 Correlation Structure among Agronomic Traits, Yield Components, and Grain Quality Attributes

The negative correlation observed between the number of spikes per m² and the number of kernels per spike reflects a compensation effect among yield components, a mechanism widely documented in wheat [95]. This compensation becomes more pronounced under abiotic stress conditions, where plants adjust reproductive allocation to optimize the use of available assimilates [96].

Under organic farming conditions, the positive association between grain yield and the number of kernels per spike indicates that yield formation depends mainly on spike fertility and grain filling capacity rather than on stand density, a pattern commonly observed in low-input systems [97]. In contrast, the relationship between semolina yield and spike number per m² suggests that grain availability contributes to processing potential, as reported by Martínez-Peña et al. [80].

The absence of significant correlations between semolina yield and thousand-grain weight confirms that semolina yield is not determined solely by agronomic yield components but also by intrinsic grain characteristics and milling aptitude [73].

The strong relationship between grain vitreousness and technological traits highlights the importance of endosperm structure in determining semolina extraction and processing quality [98]. Similarly, the

association between protein concentration and gluten index confirms that protein functionality plays a major role in gluten strength and technological performance [99].

Finally, the absence of a significant relationship between agronomic yield and protein concentration confirms the classical yield protein trade-off observed in durum wheat, a compromise that is often accentuated under organic farming due to limited and variable nitrogen availability. This explains the dissociation between productivity and protein accumulation reported in numerous studies [100].

4.6 Contribution of the PCA Biplot to the Interpretation of Yield–Quality Relationships

The PCA biplot highlights a structuring dissociation between the determinants of agronomic yield and those of technological quality, thereby confirming and synthesizing the relationships observed in the correlation matrix [101]. The clear separation along the F1 axis between quality-related variables (vitreousness, protein concentration, gluten traits, and semolina yield) and certain quantitative yield components illustrates the classical trade-off between productivity and technological quality in durum wheat [102].

The strong collinearity observed in the biplot between vitreousness, gluten-related parameters, and semolina yield indicates that these criteria constitute an integrated system, directly linked to endosperm structure and the functionality of the protein network [74,103,104]. This multivariate organization reinforces the hypothesis that vitreousness acts as a pivotal trait, simultaneously conditioning semolina extraction and gluten quality, as widely reported in recent literature [105,106].

Moreover, the projection of yield components onto a distinct axis (F2) indicates that yield construction under organic farming conditions relies primarily on physiological mechanisms related to the number of kernels per spike and the efficiency of grain filling, independently of technological quality traits [107]. This relative independence explains the absence of a significant correlation between agronomic yield and protein concentration and confirms that the simultaneous improvement of yield and quality remains a major challenge in low-input farming systems [108].

Finally, the dispersion of genotypes across the biplot reveals the existence of contrasting performance profiles, with some genotypes combining strong technological aptitude with moderate yield, while others prioritize productivity at the expense of quality [100]. This multivariate structure provides a relevant analytical framework for identifying genotypes with optimized yield–quality trade-offs, which are particularly sought after in durum wheat value chains under organic farming conditions [13,109,110].

5 Conclusions

The production of organic durum wheat remains limited in Tunisia due to agronomic and technical constraints. Nevertheless, this study demonstrates that varietal choice constitutes a key lever for reconciling productivity, yield stability, and technological quality under Mediterranean organic farming conditions, in a context of strong interannual climatic variability. The results highlight the relevance of a strategy combining stable modern varieties and well-adapted local populations, the latter being distinguished by their technological aptitude under low-input farming systems. In this regard, the identification of contrasted genetic targets Chili, Biskri, Mahmoudi, and Jenah Khotifa for grain quality, and Dhahbi, INRAT100, and Monastir for productivity and stability provides an operational basis for varietal improvement. Because grain yield, technological quality, and yield stability are complex traits that may not always be optimized simultaneously, future breeding programs should adopt a multi-trait selection approach that balances these complementary objectives rather than focusing on a single characteristic. The present results indicate that exploiting the complementary strengths of modern cultivars for productivity and stability together with

Tunisian landraces for technological quality represents a promising strategy for developing resilient durum wheat cultivars adapted to Mediterranean organic and low-input farming systems.

Furthermore, supporting stakeholders of the organic durum wheat value chain through the development of specific technical references appears essential, particularly through the establishment of a varietal catalogue integrating protein content ranges compatible with the technological requirements of pasta and couscous processing. From a breeding perspective, the development of cultivars specifically adapted to organic farming, using stable genotypes such as INRAT100 or Monastir, represents a methodologically relevant approach. Multiple crossing strategies (polycross), combining adaptation to low-input farming systems, technological quality, and yield stability thereby integrating these complementary breeding objectives, for instance INRAT100 × Mahmoudi, followed by the integration of Monastir or Dhahbi constitute credible pathways for the development of resilient cultivars and for the sustainable strengthening of organic durum wheat value chains in Mediterranean regions.

Acknowledgement: Not applicable.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Conceptualization, Anis Boukrain, Mondher Mejri; methodology, Anis Boukrain, Mondher Mejri; validation, Mondher Mejri; formal analysis, Anis Boukrain, Mondher Mejri; investigation, Anis Boukrain, Mondher Mejri; resources, Anis Boukrain, Mondher Mejri; data curation, Anis Boukrain, Mondher Mejri; writing—original draft preparation, Anis Boukrain; writing—review and editing, Anis Boukrain, Mondher Mejri; visualization, Anis Boukrain, Mondher Mejri; supervision, Mondher Mejri; project administration, Mondher Mejri; funding acquisition, Anis Boukrain, Mondher Mejri. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The data presented in this study are available on request from the corresponding author.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Supplementary Materials: The supplementary material is available online at <https://www.techscience.com/doi/10.32604/phyton.2026.085705/s1>.

References

1. Fellahi ZEA, Boubellouta T, Hannachi A, Belguet H, Louahdi N, Benmahammed A, et al. Exploitation of the genetic variability of diverse metric traits of durum wheat (*Triticum turgidum* L. ssp. durum desf.) cultivars for local adaptation to semi-arid regions of Algeria. *Plants*. 2024;13(7):934. [CrossRef].
2. Xynias IN, Mylonas I, Korpetis EG, Ninou E, Tsaballa A, Avdikos ID, et al. Durum wheat breeding in the Mediterranean region: current status and future prospects. *Agronomy*. 2020;10(3):432.
3. Mazhoud H, Chemak F, Chenoune R. Analyse typologique et performance productive de la culture du blé dur irrigué en Tunisie. *Cah Agric*. 2020;29:24.
4. Ouaja M, Bahri BA, Aouini L, Ferjaoui S, Medini M, Marcel TC, et al. Morphological characterization and genetic diversity analysis of Tunisian durum wheat (*Triticum turgidum* var. durum) accessions. *BMC Genom Data*. 2021;22(1):3. [CrossRef].
5. Yilmaz D, Ben-Nasr S, Mantes A, Ben-Khalifa N, Daghari I, Godin A. Climate change, loss of agricultural output and the macro-economy: the case of Tunisia. *AFD Res Pap*. 2023;(286):1–106.
6. Babalola KO, Monacelli N, Gozzi M, Ceccarelli S, Folloni S, Galaverna G. Genetic diversity and climate change adaptation in wheat: a systematic review of landraces, composite cross populations, and evolutionary populations. *Front Sustain Food Syst*. 2025;9:1504922. [CrossRef].

7. Grosse-Heilmann M, Cristiano E, Deidda R, Viola F. Durum wheat productivity today and tomorrow: a review of influencing factors and climate change effects. *Resour Environ Sustain*. 2024;17:100170. [[CrossRef](#)].
8. Miroslavljević M, Mikić S, Župunski V, Abdelhakim L, Trkulja D, Zhou R, et al. Effects of heat stress during anthesis and grain filling stages on some physiological and agronomic traits in diverse wheat genotypes. *Plants*. 2024;13(15):2083. [[CrossRef](#)].
9. Sabella E, Aprile A, Negro C, Nicoli F, Nutricati E, Vergine M, et al. Impact of climate change on durum wheat yield. *Agronomy*. 2020;10(6):793. [[CrossRef](#)].
10. Tita D, Mahdi K, Devkota KP, Devkota M. Climate change and agronomic management: addressing wheat yield gaps and sustainability challenges in the Mediterranean and MENA regions. *Agric Syst*. 2025;224:104242.
11. Chab L, Biagini L, Severini S. Towards an effective risk management in durum wheat production: a systematic review and bibliometric analysis of factors influencing quality and yield. *Agriculture*. 2024;14(12):2266. [[CrossRef](#)].
12. Rahman A, Baharlouei P, Koh EHY, Pirvu DG, Rehmani R, Arcos M, et al. A comprehensive analysis of organic food: evaluating nutritional value and impact on human health. *Foods*. 2024;13(2):208. [[CrossRef](#)].
13. Antichi D, Pampana S, Sbrana M, Tramacere LG, Mazzoncini M, Carlesi S, et al. Long-term evaluation of organic management of durum wheat in Central Italy. *Agron J*. 2025;117(2):e70026. [[CrossRef](#)].
14. Komor A, Pawlak J, Wróblewska W, Białoskurski S, Czernyszewicz E. Spatial differentiation of the competitiveness of organic farming in EU countries in 2014–2023: an input–output approach. *Sustainability*. 2025;17(17):7614. [[CrossRef](#)].
15. Jahn N, Konradl U, Fleissner K, Geisslitz S, Scherf KA. Protein composition in ancient wheats is determined by ploidy level. *J Cereal Sci*. 2025;123:104185. [[CrossRef](#)].
16. Sakr N. Caractérisation des variétés de blé tendre libanaises: approches agronomique, biochimique et technologique. Amiens, France: Université de Picardie Jules Verne; 2021.
17. Riar A, Sisodia B, Keller C, Patidar I, Stuerz S, Goldmann E, et al. Long-term economic and yield comparison of organic and conventional cotton-based production systems with wheat and soybean rotations in central India. *Eur J Agron*. 2025;171:127814. [[CrossRef](#)].
18. Balmford A, Amano T, Bartlett H, Chadwick D, Collins A, Edwards D, et al. The environmental costs and benefits of high-yield farming. *Nat Sustain*. 2018;1(9):477–85. [[CrossRef](#)].
19. Prashant V. Exploring sustainable agriculture practices: a comprehensive study on environmental impact and food security. *Sust Agric Food Environ Res*. 2023;12(1):1–12. [[CrossRef](#)].
20. Rezgui F, Lambarraa-Lehnhardt F, Blanc L, Plaza-Bonilla D, Lampurlanés J, Dordas C, et al. Diverging agri-environmental, social and economic impacts when diversifying Mediterranean farming systems. *J Environ Manag*. 2025;393:127040. [[CrossRef](#)].
21. Fan S, Ma Z, Wu J, Yang T, Hao J, Chen S, et al. Ecophysiological benefits of industrial organic wastes on alfalfa yield and stress mitigation in saline soils. *Ind Crops Prod*. 2025;236:121862. [[CrossRef](#)].
22. Peltoniemi K, Velmala S, Fritze H, Lemola R, Pennanen T. Long-term impacts of organic and conventional farming on the soil microbiome in boreal arable soil. *Eur J Soil Biol*. 2021;104:103314. [[CrossRef](#)].
23. Chaouachi L, Marín-Sanz M, Barro F, Karmous C. Study of the genetic variability of durum wheat (*Triticum durum* Desf.) in the face of combined stress: water and heat. *AoB Plants*. 2024;16(1):plad085. [[CrossRef](#)].
24. Sreechithra TV, Sakhare SD. Development of novel process for production of high-protein soybean semolina and its functionality. *Food Res Int*. 2025;203:115865. [[CrossRef](#)].
25. Kuru B, Menziri A, Kassa M. Genetic parameters, association of traits and selection of durum wheat genotypes (*Triticum turgidum* L. var. durum) advanced lines at Injibara, Northwestern Ethiopia. *Agrosyst Geosci Environ*. 2025;8(2):e70143. [[CrossRef](#)].
26. Paire L, McCabe C, McCabe T. Multi-model genome-wide association study on key organic naked barley agronomic, phenological, diseases, and grain quality traits. *Euphytica*. 2024;220(7):118. [[CrossRef](#)].
27. Fontaine L, Celette F, De Cordoue AL, Metais P, Cordeau S, Vacher C, et al. Mise en réseau d'expérimentations de longue durée de systèmes de grande culture en agriculture biologique: apports méthodologiques et enseignements pour des systèmes très économes en phytosanitaires. *Innov Agron*. 2018;70:317–30.
28. Elakhdar A, El-Naggar AA, El-Wakeell S, Ahmed AH. Integrating univariate and multivariate stability indices for breeding climate-resilient barley cultivars. *BMC Plant Biol*. 2025;25(1):76. [[CrossRef](#)].

29. Gharbi M, El Felah M. Article de synthèse Les céréales en Tunisie: plus d'un siècle de recherche variétale. Ann DE L'INRATT. 2013;86:45–63.
30. Ammar K, Gharbi M, Deghais M. Wheat in Tunisia. In: The world wheat book: a history of wheat breeding. Vol. 2. Paris, France: Lavoisier; 2011. p. 443–65.
31. Deghais M, Kouki M, Gharbi MS, El Felah M. Les variétés de céréales cultivées en Tunisie. Tunis, Tunisie: INRAT; 2007.
32. Ben Salem M, Daaloul A, Ayadi A. Le blé dur en Tunisie. In: Durum wheat quality in the Mediterranean region. Montpellier, France: CIHEAM; 1995. p. 81–91.
33. Saade ME. Adoption and impact of high yielding wheat varieties in northern Tunisia. Mexico City, Mexico: CIMMYT (International Maize and Wheat Improvement Center); 1996.
34. Boukrain A, Martínez-Villaluenga C, Frias J, Mejri M, Peñas E. Effect of farming system on grain composition and immunogenic potential of ancient and modern durum wheat varieties. Foods. 2026;15(7):1121. [[CrossRef](#)].
35. Finlay KW, Wilkinson GN. The analysis of adaptation in a plant-breeding programme. Aust J Agric Res. 1963;14(6):742–54. [[CrossRef](#)].
36. Eberhart SA, Russell WA. Stability parameters for comparing varieties. Crop Sci. 1966;6(1):36–40. [[CrossRef](#)].
37. Francis TR, Kannenberg LW. Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. Can J Plant Sci. 1978;58(4):1029–34. [[CrossRef](#)].
38. Wricke G. Über eine methode zur erfassung der ökologischen streubreite in feldversuchen. Z Pflanzenzucht. 1962;47:92–6. (In German).
39. Shukla GK. Some statistical aspects of partitioning genotype-environmental components of variability. Heredity. 1972;29(2):237–45. [[CrossRef](#)].
40. Plaisted RL, Peterson LC. A technique for evaluating the ability of selections to yield consistently in different locations or seasons. Am Potato J. 1959;36(11):381–5. [[CrossRef](#)].
41. Lin CS, Binns MR, Lefkovitch LP. Stability analysis: where do we stand? Crop Sci. 1986;26(5):894–900. [[CrossRef](#)].
42. ISO 712:2009. Cereals and cereal products—determination of moisture content—reference method. Geneva, Switzerland: International Organization for Standardization; 2009.
43. ISO 7971-3:2019. Cereals—determination of bulk density, called mass per hectolitre—part 3: routine method. Geneva, Switzerland: International Organization for Standardization; 2019.
44. EN 15585:2008. Cereals and cereal products—durum wheat (*T. durum* Desf.)—determination of percentage of vitreous grains and calculation of percentage of vitreous grains. Brussels, Belgium: European Committee for Standardization; 2008.
45. NF V03-050. Produits agricoles et alimentaires—directives générales pour le dosage de l'azote selon la méthode de Kjeldahl. Paris, France: Association Française de Normalisation; 1970.
46. ISO 21415-2:2015. Wheat and wheat flour—gluten content—part 2: determination of wet gluten and gluten index by mechanical means. Geneva, Switzerland: International Organization for Standardization; 2015.
47. ISO 21415-3:2006. Wheat and wheat flour—gluten content—part 3: determination of dry gluten from wet gluten by an oven drying method. Geneva, Switzerland: International Organization for Standardization; 2006.
48. ISO 15793:2000. Durum wheat semolinas—determination of the undersize fraction. Geneva, Switzerland: International Organization for Standardization; 2000.
49. Pour-Aboughadareh A, Yousefian M, Moradkhani H, Pocza P, Siddique KHM. STABILITYSOFT: a new on-line program to calculate parametric and non-parametric stability statistics for crop traits. Appl Plant Sci. 2019;7(1):e01211. [[CrossRef](#)].
50. Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. Nature. 2012;485(7397):229–32. [[CrossRef](#)].
51. Cox W, Cherney J, Sorrells M. Organic compared with conventional wheat had competitive yields during the early years of organic production in the northeast USA. Agronomy. 2019;9(7):380. [[CrossRef](#)].
52. Khaeim H, Kende Z, Balla I, Gyuricza C, Eser A, Tarnawa Á. The effect of temperature and water stresses on seed germination and seedling growth of wheat (*Triticum aestivum* L.). Sustainability. 2022;14(7):3887. [[CrossRef](#)].
53. Slafer GA, García GA, Serrago RA, Miralles DJ. Physiological drivers of responses of grains per m² to environmental and genetic factors in wheat. Field Crops Res. 2022;285:108593. [[CrossRef](#)].

54. Fernie E, Tan DKY, Liu SY, Ullah N, Khoddami A. Post-anthesis heat influences grain yield, physical and nutritional quality in wheat: a review. *Agriculture*. 2022;12(6):886. [[CrossRef](#)].
55. Devkota M, Devkota KP, Karrou M, Nangia V. Genotype and agronomic management interaction to enhance wheat yield and water use efficiency in the Mediterranean rainfed environment of Morocco: I. Field data analysis. *Eur J Agron*. 2023;151:126972. [[CrossRef](#)].
56. de la Cruz VYV, Tantriani, Cheng W, Tawaraya K. Yield gap between organic and conventional farming systems across climate types and sub-types: a meta-analysis. *Agric Syst*. 2023;211:103732. [[CrossRef](#)].
57. Zhang B, Wang S, Slater L. Anthropogenic climate change doubled the frequency of compound drought and heatwaves in low-income regions. *Commun Earth Environ*. 2024;5:715. [[CrossRef](#)].
58. Dias AS, Lidon FC. Evaluation of grain filling rate and duration in bread and durum wheat, under heat stress after anthesis. *J Agron Crop Sci*. 2009;195(2):137–47. [[CrossRef](#)].
59. Cosentino SL, Sanzone E, Testa G, Patanè C, Anastasi U, Scordia D. Does post-anthesis heat stress affect plant phenology, physiology, grain yield and protein content of durum wheat in a semi-arid Mediterranean environment? *J Agron Crop Sci*. 2019;205(3):309–23. [[CrossRef](#)].
60. Scandurra A, Corinzia SA, Caruso P, Cosentino SL, Testa G. Productivity of wheat landraces in rainfed and irrigated conditions under conventional and organic input in a semiarid Mediterranean environment. *Agronomy*. 2024;14(10):2338. [[CrossRef](#)].
61. Sharafi S, Nahvinia MJ. Sustainability insights: enhancing rainfed wheat and barley yield prediction in arid regions. *Agric Water Manag*. 2024;299:108857. [[CrossRef](#)].
62. Chacón-Vozmediano JL, Martínez-Gascuña J, García-Navarro FJ, Jiménez-Ballesta R. Effects of water stress on vegetative growth and ‘merlot’ grapevine yield in a semi-arid Mediterranean climate. *Horticulturae*. 2020;6(4):95. [[CrossRef](#)].
63. Renzetti M, Bertolini E, Trovato M. Proline metabolism genes in transgenic plants: meta-analysis under drought and salt stress. *Plants*. 2024;13(14):1913. [[CrossRef](#)].
64. Adamipour N, Nazari F, Nalouisi AM, Teixeira da Silva JA. Evaluation of the molecular mechanism underlying proline metabolic and catabolic pathways and some morpho-physiological traits of tobacco (*Nicotiana tabacum* L.) plants under arsenic stress. *BMC Plant Biol*. 2025;25(1):258. [[CrossRef](#)].
65. Bouatrous A, Harbaoui K, Karmous C, Gargouri S, Souissi A, Belguesmi K, et al. Effect of wheat monoculture on durum wheat yield under rainfed sub-humid Mediterranean climate of Tunisia. *Agronomy*. 2022;12(6):1453. [[CrossRef](#)].
66. Ouaja M, Aouini L, Bahri B, Ferjaoui S, Medini M, Marcel TC, et al. Identification of valuable sources of resistance to *Zymoseptoria tritici* in the Tunisian durum wheat landraces. *Eur J Plant Pathol*. 2020;156(2):647–61. [[CrossRef](#)].
67. Ayed S, Othmani A, Bouhaouel I, Teixeira da Silva JA. Multi-environment screening of durum wheat genotypes for drought tolerance in changing climatic events. *Agronomy*. 2021;11(5):875. [[CrossRef](#)].
68. Tahir ISA, Elbashier EME, Mustafa HM, Elhashimi AMA, Abdalla MGA, Hassan MK, et al. Durum wheat field performance and stability in the irrigated, dry and heat-prone environments of Sudan. *Agronomy*. 2023;13(6):1598. [[CrossRef](#)].
69. Ninou E, Tsivelika N, Sistanis I, Katsenios N, Korpetis E, Vazaneli E, et al. Assessment of durum wheat cultivars’ adaptability to Mediterranean environments using G × E interaction analysis. *Agronomy*. 2024;14(1):102. [[CrossRef](#)].
70. Urbanavičiūtė I, Bonfiglioli L, Pagnotta MA. Selection of durum wheat and SSR markers for organic farming in central Italy using AMMI analysis. *Agronomy*. 2024;14(3):458. [[CrossRef](#)].
71. Ziegler V, Paraginski RT, Ferreira CD. Grain storage systems and effects of moisture, temperature and time on grain quality—A review. *J Stored Prod Res*. 2021;91:101770. [[CrossRef](#)].
72. Wang K, Fu BX. Inter-relationships between test weight, thousand kernel weight, kernel size distribution and their effects on durum wheat milling, semolina composition and pasta processing quality. *Foods*. 2020;9(9):1308. [[CrossRef](#)].
73. Wang K, Taylor D, Ruan Y, Pozniak CJ, Izydorczyk M, Fu BX. Unveiling the factors affecting milling quality of durum wheat: influence of kernel physical properties, grain morphology and intrinsic milling behaviours. *J Cereal Sci*. 2023;113:103755. [[CrossRef](#)].
74. Dimitrios A. Durum wheat: uses, quality characteristics, and applied tests. London, UK: IntechOpen; 2023.

75. Moreira J, Rodrigo S, Pinheiro N, Costa R, Costa A, Dôres J, et al. Durum wheat kernel: influence of the genotype and environment on the mineral profile of grains and ashes. *Plants*. 2025;14(22):3414. [[CrossRef](#)].
76. Sieber AN, Würschum T, Longin CFH. Vitreosity, its stability and relationship to protein content in durum wheat. *J Cereal Sci*. 2015;61:71–7. [[CrossRef](#)].
77. El-Khayat GH, Samaan J, Manthey FA, Fuller MP, Brennan CS. Durum wheat quality I: some physical and chemical characteristics of Syrian durum wheat genotypes. *Int J Food Sci Technol*. 2006;41(Supplement_2):22–9. [[CrossRef](#)].
78. Moayedi S, Elias EM, Manthey FA. Effect of weather on grain quality traits of durum wheat grown in the Northern Plains of USA. *Am J Plant Sci*. 2021;12(12):1894–911. [[CrossRef](#)].
79. Melios S, Ninou E, Irakli M, Tsivelika N, Sistanis I, Papathanasiou F, et al. Effect of genotype, environment, and their interaction on the antioxidant properties of durum wheat: impact of nitrogen fertilization and sowing time. *Agriculture*. 2024;14(2):328. [[CrossRef](#)].
80. Martínez-Peña R, Rezzouk FZ, del Carmen Díez-Fraile M, Nieto-Taladriz MT, Araus JL, Aparicio N, et al. Genotype-by-environment interaction for grain yield and quality traits in durum wheat: identification of ideotypes adapted to the Spanish region of Castile and León. *Eur J Agron*. 2023;151:126951. [[CrossRef](#)].
81. Desta B, Eshetu S, Meseret A. Grain quality responses of durum wheat (*Triticum turgium* L. var. durum) to N fertilizer and seed rates. *Adv Biosci Bioeng*. 2024;12(3):50–7. [[CrossRef](#)].
82. Ryan J, Ibrikci H, Sommer R, McNeill A. Nitrogen in rainfed and irrigated cropping systems in the Mediterranean region. *Adv Agron*. 2009;104:53–136. [[CrossRef](#)].
83. Pampana S, Mariotti M. Durum wheat yield and N uptake as affected by N source, timing, and rate in two Mediterranean environments. *Agronomy*. 2021;11(7):1299. [[CrossRef](#)].
84. Ayadi S, Jallouli S, Chamekh Z, Zouari I, Landi S, Hammami Z, et al. Variation of grain yield, grain protein content and nitrogen use efficiency components under different nitrogen rates in Mediterranean durum wheat genotypes. *Agriculture*. 2022;12(7):916. [[CrossRef](#)].
85. Melki M, Samaali S, Mechri M, Saidi W. Étude qualitative et quantitative de la production du blé dur (*Triticum durum* Desf.) conduit sous différentes modalités de fractionnement de nitrate d'ammonium. *J New Sci*. 2015;20(6):810–7.
86. Benzarti Z. Contribution à l'utilisation de l'indice de nutrition azotée (INN) et des valeurs chlorophyllométriques (SPAD) pour la gestion de la fertilisation azotée du blé dur [master's thesis]. Tunis, Tunisia: Institut national agronomique de Tunis; 2009.
87. Takač V, Tóth V, Rakszegi M, Mikó P, Mikić S, Miroslavljević M. The influence of farming systems, genotype and their interaction on bioactive compound, protein and starch content of bread and spelt wheat. *Foods*. 2022;11(24):4028. [[CrossRef](#)].
88. Mitura K, Cacak-Pietrzak G, Feledyn-Szewczyk B, Szablewski T, Studnicki M. Yield and grain quality of common wheat (*Triticum aestivum* L.) depending on the different farming systems (organic vs. integrated vs. conventional). *Plants*. 2023;12(5):1022. [[CrossRef](#)].
89. Garrido-Lestache E, López-Bellido RJ, López-Bellido L. Durum wheat quality under Mediterranean conditions as affected by N rate, timing and splitting, N form and S fertilization. *Eur J Agron*. 2005;23(3):265–78. [[CrossRef](#)].
90. Landolfi V, Visioli G, Blandino M. Effect of nitrogen fertilization and fungicide application at heading on the gluten protein composition and rheological quality of wheat. *Agronomy*. 2021;11(9):1687. [[CrossRef](#)].
91. Daaloul Bouacha O, Rezgui S. Spaghetti quality: comparison between landraces and high yielding Tunisian durum wheat varieties. *J New Sci Agric Biotechnol*. 2019;64(7):4056–60.
92. Klikocka H, Szczepaniak W. Energy crisis—alternative use of winter bread wheat grain depending on protein content. *Agronomy*. 2023;13(3):861. [[CrossRef](#)].
93. Guo L, Fang F, Zhang Y, Xu D, Jin Z, Xu X. Glutathione affects rheology and water distribution of wheat dough by changing gluten conformation and protein depolymerisation. *Int J Food Sci Tech*. 2021;56(7):3157–65. [[CrossRef](#)].
94. Cecchini C, Bresciani A, Menesatti P, Pagani MA, Marti A. Assessing the rheological properties of durum wheat semolina: a review. *Foods*. 2021;10(12):2947. [[CrossRef](#)].
95. Hubert A, Gosme M, Lauri PE. Plasticité phénotypique des céréales en réponse à la culture en agroforesterie en région méditerranéenne [master's thesis]. Villeurbanne, France: Centre pour la Communication Scientifique Directe; 2017.

96. Baillot N. Distribution of the individual mass of bread wheat grain: analysis of the variability of the mass as a function of position within the ear [dissertation]. Clermont-Ferrand, France: Université Clermont Auvergne; 2019.
97. Faure J, Gaba S, Gautier JL, Leluc A, Bretagnolle V. Economic viability of reduced agricultural inputs in farmer-co-designed large-scale experimental trials in western France. *Commun Earth Environ*. 2025;6:881. [[CrossRef](#)].
98. Cabas-Lühmann P, Arriagada O, Matus I, Marcotuli I, Gadaleta A, Schwember AR. Comparison of durum with ancient tetraploid wheats from an agronomical, chemical, nutritional, and genetic standpoints: a review. *Euphytica*. 2023;219(6):61. [[CrossRef](#)].
99. Grassi S, Gulli M, Visioli G, Marti A. Gluten aggregation properties as a tool for durum wheat quality assessment: a chemometric approach. *LWT*. 2021;142:111048. [[CrossRef](#)].
100. Fontaine L, Gall CL, Gauffreteau A, Moutier N, du Cheyron P, Bernicot MH. EcoVAB-Evaluer le comportement des variétés en AB: construire aujourd'hui les outils pour demain. *Innov Agron*. 2021;84:182–202. (In French). [[CrossRef](#)].
101. Kızılgeçi F, Cebeli Z. Proximal canopy sensing of twenty-two bread wheat genotypes for nutritional quality, yield attributes and grain yield under Mediterranean climate. *Int J Agric Environ Food Sci*. 2024;8(2):347–58. [[CrossRef](#)].
102. Carucci F, Gatta G, Gagliardi A, Bregaglio S, Giuliani MM. Individuation of the best agronomic practices for organic durum wheat cultivation in the Mediterranean environment: a multivariate approach. *Agric Food Secur*. 2023;12(1):12. [[CrossRef](#)].
103. Alam M, Baenziger PS, Frels K. Emerging trends in wheat (*Triticum* spp.) breeding: implications for the future. *Front Biosci*. 2024;16(1):2. [[CrossRef](#)].
104. Benayad A, Taghouti M, Benali A, Aboussaleh Y, Benbrahim N. Nutritional and technological assessment of durum wheat-faba bean enriched flours, and sensory quality of developed composite bread. *Saudi J Biol Sci*. 2021;28(1):635–42. [[CrossRef](#)].
105. Vignola MB, Bustos MC, Vanzetti L, Andreatta AE, Pérez GT. Characterization of semolina and pasta obtained from hard hexaploid wheat (*Triticum aestivum* L.) developed through selection assisted by molecular markers. *Foods*. 2025;14(11):1990. [[CrossRef](#)].
106. Ye L, Zheng W, Li X, Han W, Shen J, Lin Q, et al. The role of gluten in food products and dietary restriction: exploring the potential for restoring immune tolerance. *Foods*. 2023;12(22):4179. [[CrossRef](#)].
107. del-Canto A, De Diego N, Sanz-Sáez Á, Štefelová N, Pérez-López U, Mena-Petite A, et al. Organic management and local genotypes for elevating yield and seed quality to confront climate change challenges. *Eur J Agron*. 2025;168:127613. [[CrossRef](#)].
108. Giordano N, Sadras VO, Correndo AA, Lollato RP. Cultivar-specific phenotypic plasticity of yield and grain protein concentration in response to nitrogen in winter wheat. *Field Crops Res*. 2024;306:109202. [[CrossRef](#)].
109. Bekaddour H, Benkerbache N, Yahiaoui S, Djenadi C, Benbelkacem A, Hebbache H, et al. Multivariate analysis of agro-morphological and quality traits of a durum wheat collection under rainfed Algerian conditions. *J Cent Eur Agric*. 2024;25(2):362–74. [[CrossRef](#)].
110. Pacheco-Andrade A, Torres ME, Cántaro-Segura H, Díaz-Morales L, Matsusaka D. Stability and yield performance of durum wheat (*Triticum durum* Desf.) genotypes across environments in southern Peru. *Int J Plant Biol*. 2025;16(4):127. [[CrossRef](#)].