seeds

MDPI

*Article*

# Harnessing Genetic Diversity and Precision Nutrient Management for Nutrient-Dense, Climate-Resilient Durum Wheat (*Triticum turgidum* L. var. *durum*) in a System-Level Approach

**Anteneh Agezew Melash [1,*], Gashaw Gismu Chakilu [2], Amare Assefa Bogale [3] and Éva Babett Ábrahám [4]**

[1] Department of Plant Science, College of Agriculture and Environmental Science, Debark University, Debark P.O. Box 90, North Gondar, Ethiopia
[2] Department of Natural Resource Management, College of Agriculture and Environmental Science, Debark University, Debark P.O. Box 90, North Gondar, Ethiopia; ggismu@yahoo.com
[3] Institute of Agronomy, Hungarian University of Agriculture and Life Sciences, 2100 Gödöllő, Hungary; amexsmart12@gmail.com
[4] Institute of Crop Sciences, Faculty of Agricultural, Food Sciences and Environmental Management, University of Debrecen, Böszörményi Street 138, 4032 Debrecen, Hungary; abraham.eva@agr.unideb.hu
* Correspondence: antenehagezew2008@gmail.com

## Abstract

Durum wheat (*Triticum turgidum* L. var. *durum*) plays a central role in global food and nutritional security, yet its grain mineral and protein quality remain highly variable across varieties and environments. This study aimed to evaluate the combined effects of varieties, nitrogen (N) fertilization, foliar zinc (Zn) and sulfur (S) application, and seasonal variation on grain macro- and micronutrients (Ca, Mg, K, Zn) and protein content, adopting a system-level approach that integrates varieties, nutrient management, and seasonal variability. We hypothesized that aligning variety selection with precision nutrient management would improve grain nutritional quality while enhancing resilience to environmental variation. Significant differences among varieties ($p < 0.05$) were observed, with the spring-sown variety Durablank exhibiting the highest grain Zn concentration (34.70 mg kg$^{-1}$) compared with MV Pelsodur (23.0 mg kg$^{-1}$) and GK Julidur (23.8 mg kg$^{-1}$), representing a 50.87% varietal difference. Grain Ca, Mg, and K varied widely across varieties and seasons, with drought in 2022 increasing grain Zn, while the wetter 2023 season enhanced Mg and K accumulation. A clear yield–protein trade-off was found, where high-yielding MV Pelsodur maintained 14.3% protein while moderate-yielding Durablank reached 16.8%. Foliar Zn and S applications significantly increased grain Zn, particularly in Zn-efficient varieties. Nitrogen fertilization at 100 kg ha$^{-1}$ improved macronutrient accumulation by 12–20% compared with 60 kg N ha$^{-1}$. Significant varieties × N × season interactions ($p < 0.01$) highlight the need for adjusted varieties -specific nutrient management strategies. Overall, the findings demonstrate that integrating genetic selection with optimized fertilization and season-responsive management practices may contribute to improving grain nutritional quality of durum wheat.

**Keywords:** durum wheat; grain nutritional quality; zinc biofortification; nitrogen fertilization; foliar zinc and sulfur; varieties × environment interaction; macro- and micronutrients; protein content



Academic Editor: Jian Zhang

Received: 23 December 2025
Revised: 26 March 2026
Accepted: 26 March 2026
Published: 30 March 2026

## 1. Introduction

Durum wheat (*Triticum turgidum* L. var. *durum*) is a foundational cereal crop cultivated across many regions of the world, accounting for about 5% of global wheat production with an average annual yield of approximately 40 million tonnes from nearly 16 million hectares of cultivated land [1]. As the principal source of semolina used in pasta, couscous, and a wide variety of traditional flatbreads, durum wheat holds increasing economic and nutritional importance, likely driven by population growth, dietary diversification, and the rising demand for high-quality grain [2]. Along with its industrial and culinary value, durum wheat provides essential nutrients that support human health, placing it at the center of discussions on sustainable food systems and nutrition security. In countries where cereal-based diets dominate, micronutrient malnutrition, commonly termed "hidden hunger" remains a pervasive public-health challenge. Iron (Fe), zinc (Zn), calcium (Ca), magnesium (Mg), and phosphorus (P) are crucial for cognitive development, immune function, enzymatic processes, and overall metabolic balance [3,4], yet their concentrations in wheat grains frequently fall short of recommended dietary intake levels among vulnerable populations [5]. This nutritional gap demands research investments that enhance grain quality and promote resilient agricultural systems capable of uplifting nutritional outcomes without imposing dietary or economic burdens on marginalized communities.

The mineral composition of durum wheat grain reflects an interaction among genetic factors, soil nutrient pools, climatic influences, and management practices. Genetic variation among durum varieties offers substantial potential for improving nutrient acquisition, translocation, and partitioning into the grain. A meaningful diversity in grain Fe and Zn concentrations among elite germplasm and landraces have been previously reported, reinforcing opportunities for selective breeding and genotypic advancement [6]. Alongside genetic diversity, agronomic inputs shape grain nutrient status. Nitrogen fertilization not only governs grain yield and protein levels but also influences physiological pathways linked to remobilization of micronutrient transport within plant tissues [7]. Micronutrient applications, particularly zinc and sulfur, enhance enzyme activity, protein synthesis, and phloem mobility, ultimately strengthening nutrient loading mechanisms within developing grains. Integrated nutrient supply strategies therefore create opportunities for sustainable biofortification and nutrient-efficient varietal selection, if crop responses are thoroughly understood in representative field environments.

Environmental variability adds another layer of complexity to grain mineral dynamics because fluctuations in rainfall and soil moisture status directly affect nutrient uptake, soil nutrient mobility, and the physiological processes that control nutrient transport from roots to grain. Studies showed that drought stress reduces moisture in the soil and lowers root absorption rates for key nutrients like nitrogen and phosphorus, resulting in decreased nutrient uptake even if plant growth continues [8]. Meta-analyses have shown that terminal and continuous drought significantly decrease grain yield and protein yield but often increase grain protein concentration, a response linked to reduced carbohydrate accumulation under water deficit and changes in source–sink dynamics during grain filling [9]. Under more favorable moisture conditions, nutrient mobilization are improved, but greater biomass production and yield expansion can dilute mineral concentrations in grain if nutrient supply does not keep pace with growth [10]. These responses highlight the challenge of maintaining grain quality under increasing climate variability and the need for breeding and agronomic strategies that promote stable nutrient uptake and allocation. Durum wheat productivity and grain nutritional quality are strongly influenced by the interaction of varieties, nutrient management, and environmental conditions. Seasonal variation, such as drought or excessive rainfall, can strongly affect grain mineral concentrations, often outweighing management effects [7]. A system-level perspective

https://doi.org/10.3390/seeds5020021

that integrates genetic diversity with precision nitrogen and foliar micronutrient management allows evaluation of varieties × management × environment interactions and their impact on grain nutritional quality. Varieties with enhanced nutrient-use efficiency and resilience to variable water and nutrient availability are particularly valuable for producing nutrient-dense, climate-resilient wheat, even under well-managed but environmentally variable conditions. Multi-season trials under contrasting growing conditions reveal critical interactions among varieties, nutrient management, and environment, providing insights to guide climate-smart breeding and agronomic strategies. The study was therefore aimed at evaluating the performance, protein content, and grain mineral composition of selected durum wheat varieties under varying nitrogen and micronutrient management across contrasting seasonal environments.

## 2. Materials and Methods

### 2.1. Planting Materials

A total of ten durum wheat varieties from Austria, Slovakia, and Hungary were included in the field experiment, of which five varieties representing both spring- and winter-sown types were selected for detailed mineral composition analysis based on their high yield potential, stress tolerance, and superior grain quality. Spring-sown varieties are characterized by their rapid growth cycle, while winter-sown types benefit from extended growing periods and enhanced stress tolerance. These varieties vary in yield potential, disease resistance, drought tolerance, and grain quality, making them suitable for different management practices and climatic conditions. To provide a clear comparison, Table 1 summarizes their key agronomic characteristics.

**Table 1.** Agronomic Characteristics of the Tested Durum Wheat Varieties.

| Varieties | Growth Habit | Maturity | Key Traits |
|---|---|---|---|
| **Durablank *** | Spring | Mid–late | High yield potential, good tillering, stable performance, responsive to agronomic inputs, good grain quality |
| **Duragold *** | Spring | Mid–late | High yield potential, good tillering, stable performance, responsive to agronomic inputs, good grain quality |
| **Tamadur** | Spring | Mid | Good agronomic performance, high grain quality, disease tolerance |
| **Colliodur** | Spring | Mid | High yield potential, drought tolerance, suited to water-limited conditions |
| **MV Pennedur** | Winter | Early–mid | High yield potential, strong gluten properties, stable performance, suitable for pasta production |
| **MV Pelsodur *** | Winter | Early | High yield potential, good pasta quality, stress tolerance, high pigment content, cold tolerance, susceptible to lodging under high fertility or wet conditions |
| **MV Vékadur** | Winter | Early | High yield potential, good pasta quality, resistance to rust and fusarium, may lodge under certain conditions |
| **MV Hundur** | Winter | Mid | Tolerant to environmental stress, suitable for low-input conditions |
| **GK Julidur *** | Winter | Medium | Winter hardiness, drought tolerance, resistance to leaf and yellow rust, broad adaptation |
| **GK Betadur *** | Winter | Mid | Stable growth, drought tolerance during later stages, suited to semi-arid conditions |

Note: The asterisks (*) indicate varieties selected for detailed mineral composition analysis only. All ten varieties were included in the field experiment, but mineral profiling was conducted on this subset based on preliminary screening, seed availability, and agronomic performance.

### 2.2. Description of the Study Area

#### 2.2.1. Soil Conditions

The study was conducted at the Látókép Research Center, University of Debrecen, Hungary (47°33′42″ N, 21°27′02″ E), approximately 15 km from Debrecen [11]. The soil at the site is calcareous chernozem soil, with a humus content of 2.7–2.8%, a near-neutral pH of 6.46 (pH KCl), and a plasticity index (KA) of 40. Soil analysis indicated AL-soluble phosphorus of 57 mg $kg^{-1}$, AL-soluble potassium of 199 mg $kg^{-1}$, zinc of 0.94 mg $kg^{-1}$, and sulfur content of 0.1 mg $kg^{-1}$. Soil samples were collected from a depth of 0–20 cm at multiple locations prior to nutrient application. The water management characteristics of the soil were found to be favourable.

#### 2.2.2. Climatic Conditions

Monthly rainfall and temperature were recorded at the Látókép experimental site during the 2021–2023 growing seasons (Figure 1A,B). Considerable variation in precipitation was observed across the years. The 2021 season experienced low rainfall during several key months, resulting in relatively dry conditions. In contrast, 2023 received higher rainfall in multiple months, while 2022 showed intermediate precipitation levels. Although October received above-average rainfall (60 mm, compared to 41 mm), the subsequent months, including March (14.4 mm) and April (27.7 mm), saw much lower-than-average rainfall, contributing to drought conditions that likely limited crop productivity. Despite higher rainfall in January (69.8 mm) compared to the average (29.2 mm), the overall precipitation pattern throughout the year led to unfavorable conditions for crop growth. In contrast, 2022 was also affected by drought, with particularly low rainfall in February (8.4 mm, compared to 35.2 mm) and May (9.9 mm, compared to 54.3 mm), although some months, such as November (49.3 mm), received above-average rainfall (Figure 1A).

Nonetheless, 2022 was not as severely dry as 2021, but it still posed challenges for durum wheat production due to inconsistent moisture availability. 2023, on the other hand, was a wetter year, with several months receiving above-average rainfall. December (102.9 mm), March (59.2 mm), and June (84.5 mm) all recorded significantly higher rainfall than the 30-year average, resulting in more favorable conditions for crop growth and potentially improving yield prospects. The wetter conditions observed in 2023, particularly during critical growth periods, provided more favorable moisture conditions during that growing season compared with the drier conditions recorded in the previous years. Weather conditions during each growing season were recorded and linked to specific durum wheat growth stages according to the BBCH scale. In 2023, higher precipitation coincided with stem elongation (BBCH 30–39) and grain filling (BBCH 71–89), which are critical stages for nutrient accumulation and protein synthesis in grains. In contrast, the drier conditions in the previous seasons occurred during heading (BBCH 50–59) and early grain filling, stages particularly sensitive to water stress.

Temperature trends were generally consistent with the rainfall patterns, although with notable deviations (Figure 1B). In 2021, temperatures were slightly higher than average in several months, such as October (14 °C, compared to the 30-year average of 10.4 °C), which likely increased evapotranspiration and exacerbated the dry conditions. Despite these warmer temperatures, the limited rainfall in key growing months contributed to a challenging year for crop production. In 2022, temperatures showed more variability, with January (−0.5 °C) and February (4.1 °C) both cooler than the long-term averages, which might have slowed crop development early in the season. However, the warmer-than-average temperature in June (23.1 °C) likely supported growth during the later stages. 2023 exhibited generally warmer temperatures, particularly in January (4.4 °C) and February (2.3 °C), which may have facilitated crop growth, especially when coupled with the higher rainfall levels. The combination of warmer temperatures and abundant rainfall in 2023 likely created optimal conditions for crop development, contrasting with the more extreme conditions experienced in the prior years. In general, the comparison of rainfall and temperature data across these three years illustrates the significant variability in climatic conditions and their potential impact on crop production. 2021 was a dry year with limited rainfall, leading to adverse growing conditions, while 2022 also experienced drought-like conditions, although to a lesser extent. On the other hand, 2023 benefitted from above-average rainfall in critical months, creating favorable conditions for crop growth.

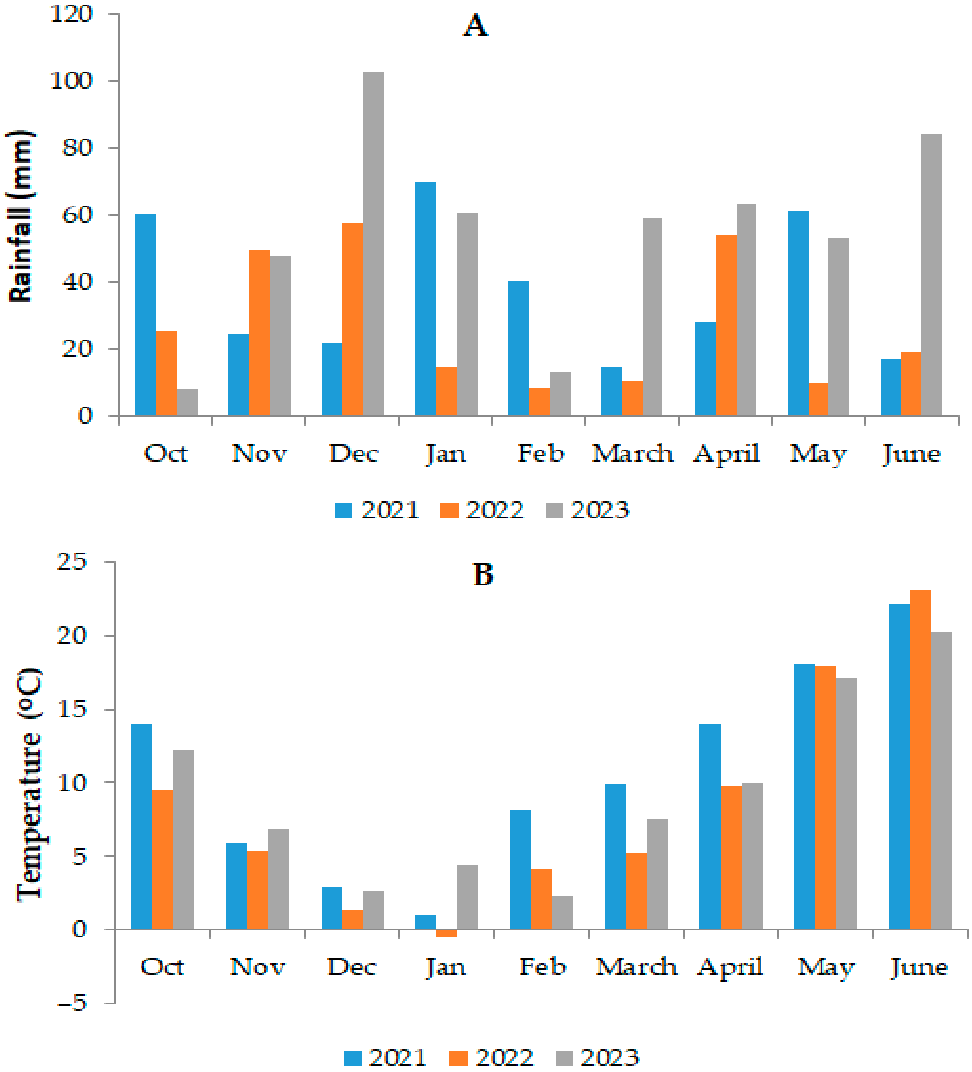


**Figure 1.** Illustrates the average monthly meteorological data such as rainfall (**A**), and temperature (**B**), recorded at the Látókép experimental site throughout the 2021–2023 cropping seasons, providing a comparative analysis against meteorological data.

*2.3. Agrotechnical Conditions of the Field Experiment*

The field experiment was conducted during the 2021/2022 and 2022/2023 growing seasons under uniform agronomic management. Soil preparation consisted of disc harrowing followed by field cultivation prior to sowing. Winter varieties were sown in mid-October and spring varieties in mid-March according to regional recommendations. Winter varieties were sown in mid-October (19 October 2021, 13 October 2022), and spring varieties in mid-March (18 March 2022, 14 March 2023). Therefore, sowing was neither delayed nor premature in either season, allowing for normal crop establishment and development.

Nitrogen fertilization was applied in split doses, with basal and top-dress applications adjusted to crop growth stages, and foliar fungicide treatments were administered at key phenological phases to maintain plant health. Herbicides and insecticides were applied as needed to control weeds and pests. Harvesting was carried out at full physiological maturity (BBCH 89). In 2022, winter and spring varieties were harvested separately based on maturity, while in 2023 all varieties were harvested on 17 July. Maize and sweet corn served as preceding crops in 2021–2022 and 2022–2023, respectively, reflecting realistic crop-rotation conditions and contributing to baseline soil nutrient dynamics.

### 2.4. Experimental Design and Treatments

The experimental treatments consisted of varying nitrogen application levels (60 kg and 100 kg $ha^{-1}$), ten durum wheat varieties, and three foliar-based fertilizer treatments (control, zinc, and sulfur) A zero-N control was not included, as the study aimed to evaluate integrated nitrogen and micronutrient management at practical field rates across the tested varieties. Treatments were arranged in a split–split plot design with three replications to ensure robust statistical inference. Nitrogen application rates were assigned to the main plots, the ten durum wheat varieties to the subplots, and the three foliar fertilizer treatments to the sub-sub plots. The subplot size was standardized at 9 m in length and 1.5 m in width (13.5 $m^2$), with 15 cm row spacing. Each plot was bordered by other wheat plots, extending at least one meter in all directions to minimize border effects. A liquid solution of sulfur and zinc, applied foliarly at the flag leaf stage, was used as fertilizers at rates of 4 L $ha^{-1}$ for sulfur and 3 L $ha^{-1}$ for zinc. Nitrogen was applied in split doses, with the first half applied at the early tillering stage and the second half applied at the tillering stage.

### 2.5. Data Collection Procedures and Measurements

The measurements included a broad spectrum, ranging from macroscopic parameters such as crop yield and size to intricate assessments of grain quality, including nutritional composition, resilience to stressors, and other attributes vital to durum wheat productivity. These parameters were devised and fine-tuned to simulate real-world agricultural scenarios while maintaining experimental rigor throughout the extensive period of research as the detailed describes as follows.

#### 2.5.1. Grain Protein Content (%) Determination

The grain protein and moisture content analysis was performed using the Pfeuffer Granolyser NIR, a sophisticated instrument developed by Pfeuffer in Germany. This machine utilizes near-infrared (NIR) diode technology, which is highly effective for assessing the composition of grain samples. During the analysis, the Pfeuffer Granolyser NIR conducts a comprehensive scan of the grain samples, performing a total of 1500 individual scans per measurement. This extensive scanning process ensures high accuracy and reliability in determining the protein and moisture content of the grains. The protein content of the grain was adjusted to a standard moisture content of 14%, ensuring consistency and comparability of results across different samples.

#### 2.5.2. Elemental Composition Analysis of the Grain

A chemical analysis was conducted to determine the elemental composition of durum wheat grain, specifically measuring aluminum (Al), boron (B), barium (Ba), calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), phosphorus (P), sulfur (S), strontium (Sr), and zinc (Zn), was analyzed using a PerkinElmer Optima 3300 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (PerkinElmer Inc., Waltham, MA, USA). This high-resolution instrument, equipped with an echelle grating system, facilitates the simultaneous quantification of multiple elements.

The sample grain was first finely ground for consistency before undergoing a two-step wet acid digestion process. In the initial predigestion stage, 1 g of the ground sample was placed in a digestion tube, and 10 mL of concentrated nitric acid ($HNO_3$, 69% $v/v$) (VWR International Ltd., Radnor, PA, USA) was added. The mixture was left to react for 12 h, after which the tubes were heated at 60 °C for 30 min using a LABOR MIM OE-718/A block digestion apparatus. Once cooled slightly, 3 $cm^3$ of hydrogen peroxide ($H_2O_2$, 30% $v/v$) (VWR International Ltd., Radnor, USA) was introduced to aid in organic matter decomposition. The main digestion phase followed, with the temperature increased to 120 °C for 90 min. Upon completion, the digested samples were allowed to cool before being diluted to a final volume of 50 $cm^3$ with ultrapure water (Milli-Q two-level purification system, Millipore S.A.S, Molsheim, France). The solution was then filtered using Filtrak 388 filter paper to remove any remaining particulates. The resulting filtrates were subsequently analyzed using ICP-OES, ensuring accurate and concurrent determination of all 18 target elements in the grain samples.

### *2.6. Statistical Data Analysis*

Data were analyzed using a split–split plot design with three replications, where varieties was assigned to main plots, nitrogen fertilization to subplots, and foliar micronutrient treatments to sub-subplots. The hierarchical structure of the experimental design was accounted for in the analysis, and each factor and interaction was tested using the appropriate error term corresponding to its level in the design. Varieties, nitrogen fertilization, and micronutrient treatments were considered fixed effects, while year (season) was treated as a random effect to account for environmental variability across seasons. Analysis of variance (ANOVA) was performed using GenStat software (18th ed.) [12] to evaluate the main effects and their interactions, including varieties × nitrogen × micronutrient × year. When significant differences were detected, treatment means were compared using the least significant difference (LSD) test at $p \leq 0.05$. Results are presented as mean values, with error bars representing the standard error (SE) of the mean difference.

Pearson's correlation coefficients were calculated to examine relationships among measured traits. The strength of correlations was interpreted according to Evans [13], where the absolute value of the correlation coefficient (r) is classified as very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and very strong (0.80–1.00).

## 3. Results

### *3.1. Varietal-Environment Interaction Effects on Grain Protein Content*

A comprehensive understanding of the dynamics affecting grain protein content in durum wheat is crucial for optimizing both crop quality and yield. Analysis of variance revealed that interaction effects of nitrogen application combined with varietal differences, and foliar zinc and sulfur applications were statistically significant ($p < 0.05$) in influencing grain protein levels (Table 2; Figure 2). However, the main effects of zinc, sulfur, and nitrogen alone did not significantly ($p < 0.05$) impact grain protein content, indicating that their combined influence is more critical than their individual effects. The significant ($p < 0.05$) interaction between nitrogen application and varietal differences indicates the importance of adjusting nitrogen rates to specific durum wheat varieties to optimize protein content.

The maximum grain protein content was recorded in the variety GK Julidur, which achieved 16.55% protein when sulfur was combined with a high nitrogen rate, and 16.36% when zinc was combined with a high nitrogen rate (Table 2). MV Vékadur followed, reaching 16.20% protein content under similar conditions. In contrast, MV Pelsodur consistently showed the lowest grain protein content across all nutrient treatments, 14.20% with sulfur and 13.97% with zinc combined with a high nitrogen rate, despite its high-yielding potential (Table 2).

**Table 2.** The interaction effect of nitrogen application rate, nutrient application and variation in genetic difference among durum wheat varieties on grain yield (kg ha$^{-1}$) and protein content (%).

| Varieties | 60 (kg N ha$^{-1}$) | | | | | | 100 (kg N ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Control | Sulfur | Zinc | Control | Sulfur | Zinc | Control | Sulfur | Zinc | Control | Sulfur | Zinc |
| | Grain Yield (kg ha$^{-1}$) | | | Protein Content (%) | | | Grain Yield (kg ha$^{-1}$) | | | Protein Content (%) | | |
| GK Bétadur | 6157.68 | 5348.48 | 5606.23 | 15.18 | 15.44 | 15.36 | 5019.62 | 4980.40 | 4001.34 | 15.94 | 16.00 | 15.57 |
| GK Julidur | 6639.24 | 6350.91 | 6059.18 | 14.89 | 14.97 | 15.51 | 5063.94 | 6797.14 | 4851.26 | 16.71 | 16.36 | 16.55 |
| MV Hundur | 6403.65 | 6713.04 | 6413.99 | 15.05 | 14.57 | 15.07 | 5538.83 | 6675.87 | 5913.90 | 15.87 | 15.70 | 15.88 |
| MV Pelsodur | 7232.09 | 7638.46 | 7631.62 | 13.98 | 15.00 | 14.41 | 6768.47 | 8009.04 | 7539.44 | 14.36 | 14.20 | 13.97 |
| MV Pennedur | 6743.59 | 6189.11 | 6225.58 | 14.75 | 15.43 | 15.16 | 5884.72 | 6743.68 | 6713.29 | 14.56 | 15.50 | 15.02 |
| MV Vékadur | 6369.07 | 6311.04 | 6690.10 | 14.90 | 14.23 | 14.15 | 5965.24 | 7167.69 | 6075.47 | 15.48 | 15.44 | 16.20 |
| Durablank | 4101.09 | 4775.46 | 4899.73 | 15.66 | 15.92 | 15.81 | 4903.17 | 5031.79 | 5100.16 | 15.38 | 15.57 | 15.11 |
| Duragold | 4720.04 | 5340.67 | 5209.38 | 15.50 | 14.91 | 14.87 | 5458.32 | 5792.33 | 5337.48 | 15.76 | 15.37 | 15.88 |
| Tamadur | 4171.82 | 4307.27 | 4265.00 | 13.96 | 14.92 | 14.84 | 5255.71 | 5848.94 | 5523.70 | 14.73 | 15.51 | 14.85 |
| $LSD_{0.05}$ | 503.440 | 503.440 | 503.440 | 1.13 | 1.13 | 1.13 | 503.440 | 503.440 | 503.440 | 1.13 | 1.13 | 1.13 |
| CV (%) | 5.80 | 5.80 | 5.80 | 3.5 | 3.5 | 3.5 | 5.80 | 5.80 | 5.80 | 3.5 | 3.5 | 3.5 |

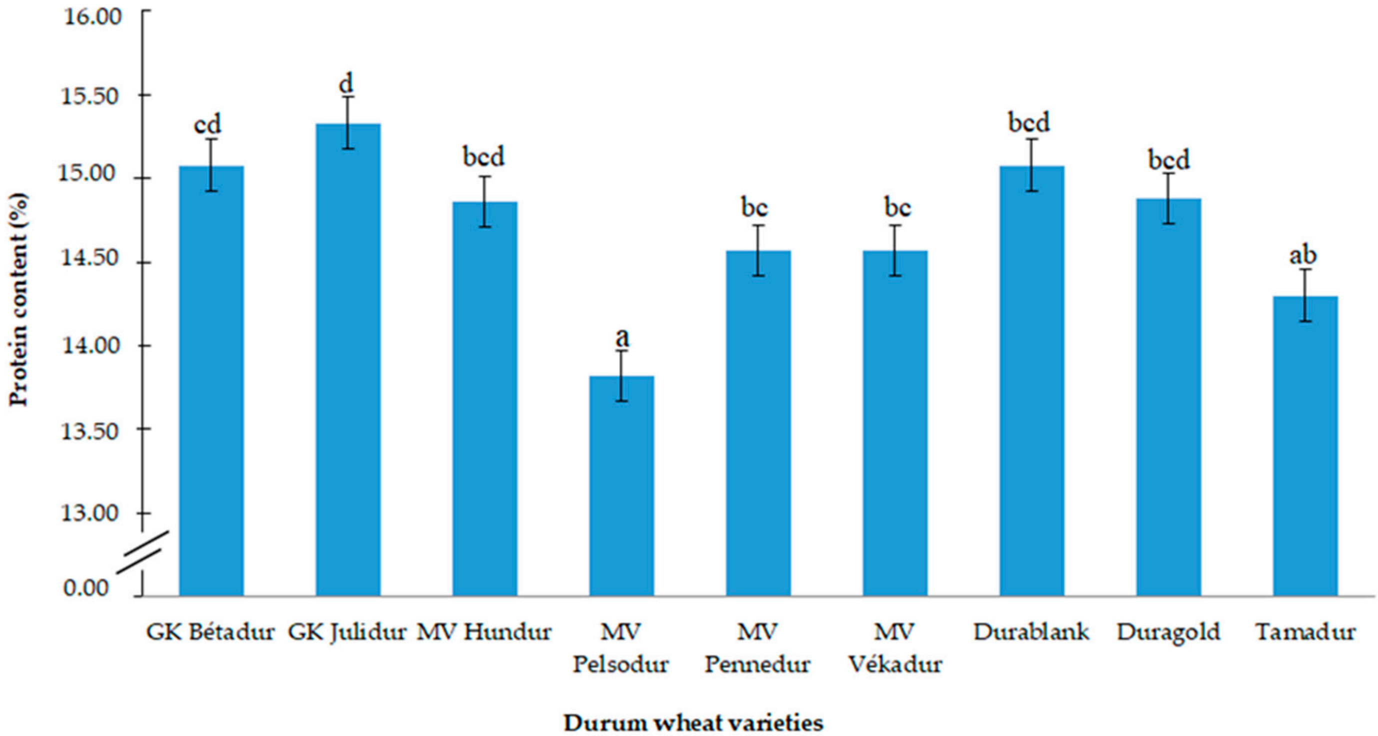


**Figure 2.** Main effect of durum wheat varieties on grain protein content at Debrecen-Látókép, 2022–2023 cropping season. Values are means of three replicates ± standard error (SE) calculated from the pooled error term of the split–split plot ANOVA. Bars with different letters are significantly different at $p < 0.01$ (LSD test), while bars with the same letters are not. The y-axis starts at 13 for visual clarity. Pooled means are presented for descriptive purposes only; due to the significant varieties × cropping season interaction (Figure 3) and changes in varieties ranking between seasons, these averages should not be interpreted as season-independent superiority.

Protein content (%) differed significantly ($p < 0.01$) among the evaluated durum wheat varieties (Figure 2). The highest protein content was recorded in GK Julidur (approximately 15.8%), followed closely by GK Bétadur (about 15.6%). These two varieties exhibited statistically higher protein content compared with most of the other varieties. Relatively high protein levels were also observed in Durablank, Duragold, and MV Hundur, with values ranging from approximately 15.3% to 15.6%. MV Pennedur and MV Vékadur showed moderate protein contents of around 15.0%, which were lower than the top-performing varieties but higher than the lowest ones. The lowest protein content was recorded in MV Pelsodur (approximately 14.3%), followed by Tamadur (around 14.8%).

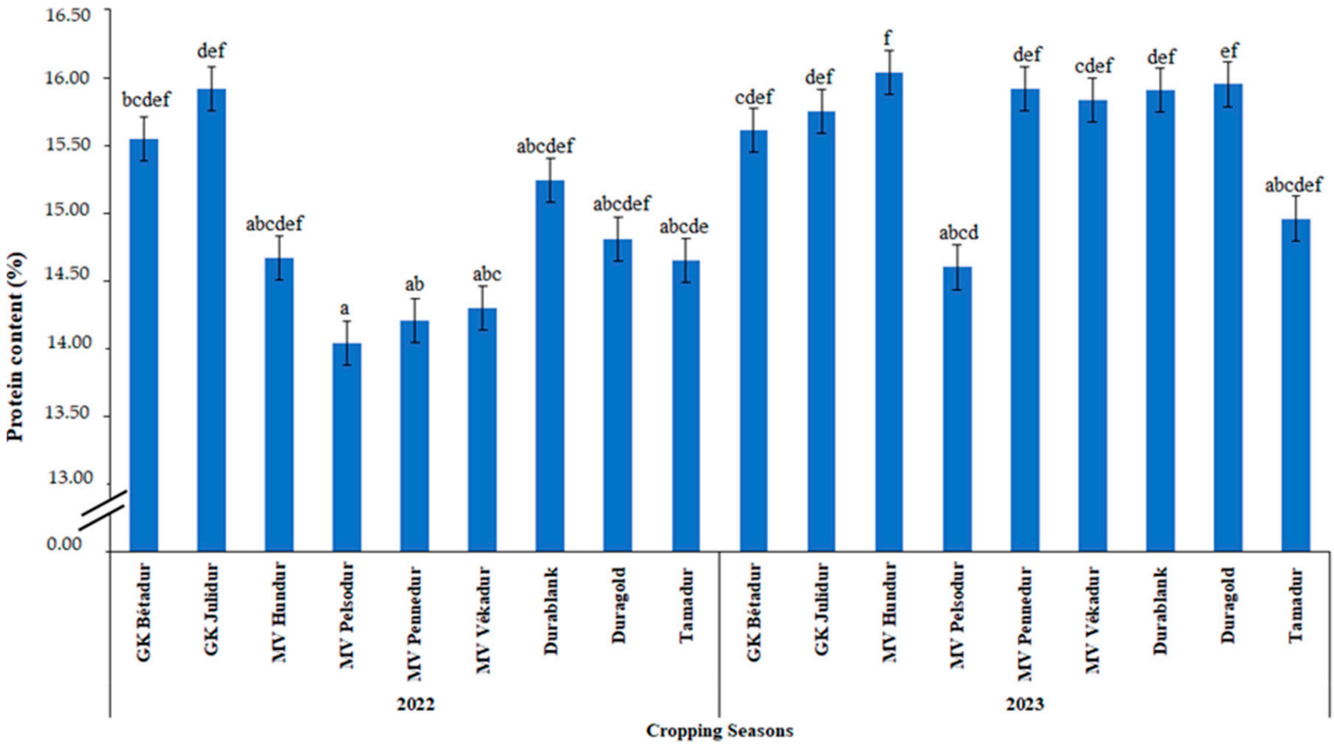


**Figure 3.** Varieties × cropping season interaction for grain protein content at Debrecen-Látókép, 2022–2023. Values are means ± standard error. The interaction was significant ($p < 0.05$), indicating that varieties performance varied between seasons. Bars with different letters are significantly different at $p < 0.05$; bars with the same letter are not. This highlights season-dependent responses and crossover in varieties ranking.

Analysis of variance showed that grain protein content in durum wheat was significantly ($p < 0.05$) influenced by the interaction between genetic variability and seasonal conditions across different cropping seasons. In the 2023 cropping season, the highest protein content was recorded in MV Hundur (16.04%), Duragold (15.95%), and Durablank (15.91%), whereas in 2022, GK Julidur (15.92%), GK Bétadur (15.55%), and Durablank (15.24%) performed best (Figure 3). Although the overall protein content was higher during 2023, variation among the tested varieties was more pronounced in 2022 (13.39%) compared to 7.22% in 2023 (Figure 3), indicating that drier conditions in 2022 amplified genetic differences, while more favorable conditions in 2023 allowed for more uniform protein accumulation. Analysis of variance further confirmed that both growing season and genetic background significantly ($p < 0.05$) affected grain protein content. The maximum difference between the two seasons was 5.40%, while variation among varieties reached 10.54% (Figure 3).

Environmental conditions, particularly water availability, along with varietal differences, significantly ($p < 0.01$) influenced grain protein content in durum wheat. The wetter 2023 season resulted in a significantly higher protein content (15.62%) compared with the drier 2022 season (14.82%) (Figure 4).

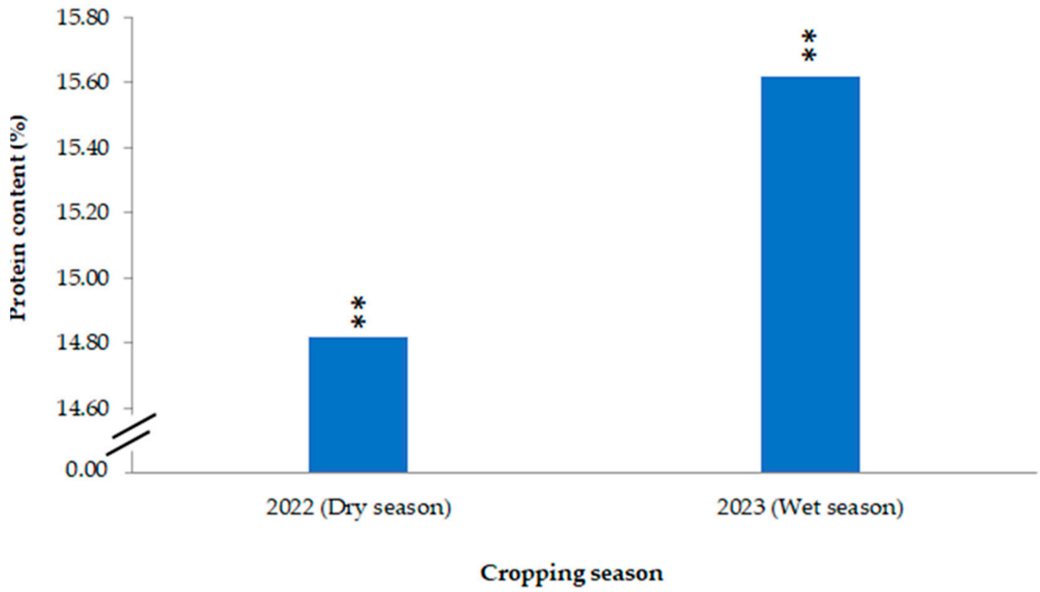


**Figure 4.** Main effect of cropping season on grain protein content of durum wheat at Debrecen-Látókép, 2022–2023, averaged across all varieties. Values are means of three replicates ± standard error (SE). Bars marked with two asterisks (**) indicate a statistically significant difference at $p < 0.001$ (LSD test).

### *3.2. Nutritional Responses to Fertilization, Variety, and Seasonal Variation*

The analysis of grain nutritional composition revealed significant ($p < 0.05$) variability among varieties, nitrogen levels, fertility treatments, and growing seasons. Varietal effects were particularly pronounced, with certain varieties consistently exhibiting higher concentrations of essential minerals such as calcium, potassium, magnesium, zinc, and iron across treatments and seasons (Supplementary Table S1). In contrast, MV Pelsodur generally showed lower mineral accumulation, confirming substantial inherent differences in nutrient acquisition and partitioning among varieties. Nitrogen application and seasonal conditions also significantly ($p < 0.05$) modulated mineral concentrations, although the relative ranking of varieties remained largely consistent. These results demonstrate that genetic background was a primary determinant of baseline grain nutrient composition under the tested agronomic conditions. Fertility treatments had a significant ($p < 0.05$) and pronounced impact on grain nutritional composition. Sulfur application significantly increased macronutrient concentrations, with calcium, potassium, and magnesium rising by 12–13% relative to the control, whereas zinc application primarily enhanced grain zinc content by approximately 25% (Supplementary Tables S1 and S2). Control plots without supplemental micronutrients consistently exhibited lower nutrient levels, confirming that baseline soil fertility limited maximum nutrient accumulation. When nitrogen fertilization was combined with either sulfur or zinc, grain nutrient concentrations were further amplified.

Significant ($p < 0.05$) interactions between nitrogen application rates and varieties were observed. High nitrogen rates consistently increased the accumulation of macro- and micronutrients in responsive varieties such as Durablank and GK Julidur, whereas varieties like MV Pelsodur showed a smaller response. For example, at 100 kg N $ha^{-1}$, Durablank accumulated 19.5% more potassium and 28.4% more magnesium than MV Pelsodur, demonstrating substantial varieties differences in nutrient use efficiency (Supplementary Table S2). These results indicate that optimized nitrogen management is critical for achieving peak nutrient concentrations in high-performing varieties.

Seasonal variation also significantly ($p < 0.05$) influences grain nutrient composition. The 2023 cropping season, characterized by higher rainfall and favorable environmental conditions, produced grains with significantly higher nutrient levels than the drier 2022 season. At 100 kg N ha$^{-1}$, potassium and magnesium increased by 29.6% and 49.2%, respectively, from 2022 to 2023, and grain protein and micronutrient concentrations (zinc, copper, iron) were similarly elevated (Supplementary Table S3). Nitrogen × season interactions were statistically significant ($p < 0.05$), demonstrating that the efficiency of nitrogen uptake and nutrient accumulation is closely linked to seasonal environmental conditions.

Analysis of variance further revealed that complex interactions among nitrogen rate, fertility treatments, variety, and growing season significantly ($p < 0.05$) influenced grain nutritional composition. High nitrogen rates combined with sulfur or zinc application during the favorable 2023 season produced the highest nutrient accumulation in responsive varieties such as Durablank, Duragold, and GK Julidur, whereas nutrient accumulation was lower across all varieties in the drier 2022 season. Genotypic variability was also more pronounced under environmental stress; for example, grain protein content differed by 13.4% among varieties in 2022 compared with 7.2% in 2023 (Figure 4).

The interaction between nitrogen and sulfur dynamics was particularly notable. While most macronutrients significantly ($p < 0.05$) increased with higher nitrogen application, maximum grain sulfur content was observed at 60 kg ha$^{-1}$ nitrogen rates, suggesting that high nitrogen may partially constrain sulfur accumulation. These results highlight the importance of coordinating nitrogen and micronutrient management to optimize grain nutritional quality under varying seasonal conditions (Supplementary Tables S1–S3).

### *3.3. Genetic and Environmental Influences on Grain Zinc Concentration*

Analysis of variance showed that grain protein content Analysis of grain zinc concentrations revealed substantial variability among the tested durum wheat varieties, highlighting the combined influence of varieties, environmental conditions, and agronomic management. Durablank consistently accumulated the highest zinc levels across treatments, averaging 34.7 mg kg$^{-1}$, whereas MV Pelsodur and GK Julidur exhibited lower concentrations, averaging 23.0 and 23.8 mg kg$^{-1}$, respectively (Figure 5). The relative difference in zinc accumulation among varieties was approximately 50.9%, and these varietal differences were statistically significant ($p < 0.01$). Nitrogen and micronutrient fertilization also significantly influenced zinc concentrations ($p < 0.05$), with higher nitrogen rates and zinc application enhancing grain zinc content, particularly in responsive varieties.

The interaction between cropping year and varietal performance significantly influenced zinc accumulation. During the drought year of 2022, Durablank achieved its peak zinc concentration of 35.79 mg kg$^{-1}$, while MV Pelsodur and GK Julidur recorded 24.84 mg kg$^{-1}$ and 24.63 mg kg$^{-1}$, respectively. In the wetter season of 2023, Durablank maintained superior zinc levels at 33.61 mg kg$^{-1}$, whereas the other varieties again lagged behind (Figure 6). Across all varieties, grain zinc concentration was generally higher during the dry year than during the wet year, suggesting that water availability and environmental stress play a crucial role in modulating zinc accumulation. The variation between varieties increased from 45.31% during the dry season to 58.99% during the wet season.

Foliar application of zinc and sulfur significantly influenced grain zinc concentrations across varieties ($p < 0.05$). Zinc application increased zinc accumulation in all varieties, but the magnitude of response was strongly varietal-dependent. Durablank exhibited the highest zinc content under foliar zinc treatment, achieving levels approximately 40% higher than the control, whereas MV Pelsodur showed minimal response under the same fertilization regime (Figure 7). These differences highlight the strong varietal capacity for zinc uptake and translocation in Durablank, whereas zinc-inefficient varieties may require more intensive management to reach comparable micronutrient levels.

https://doi.org/10.3390/seeds5020021

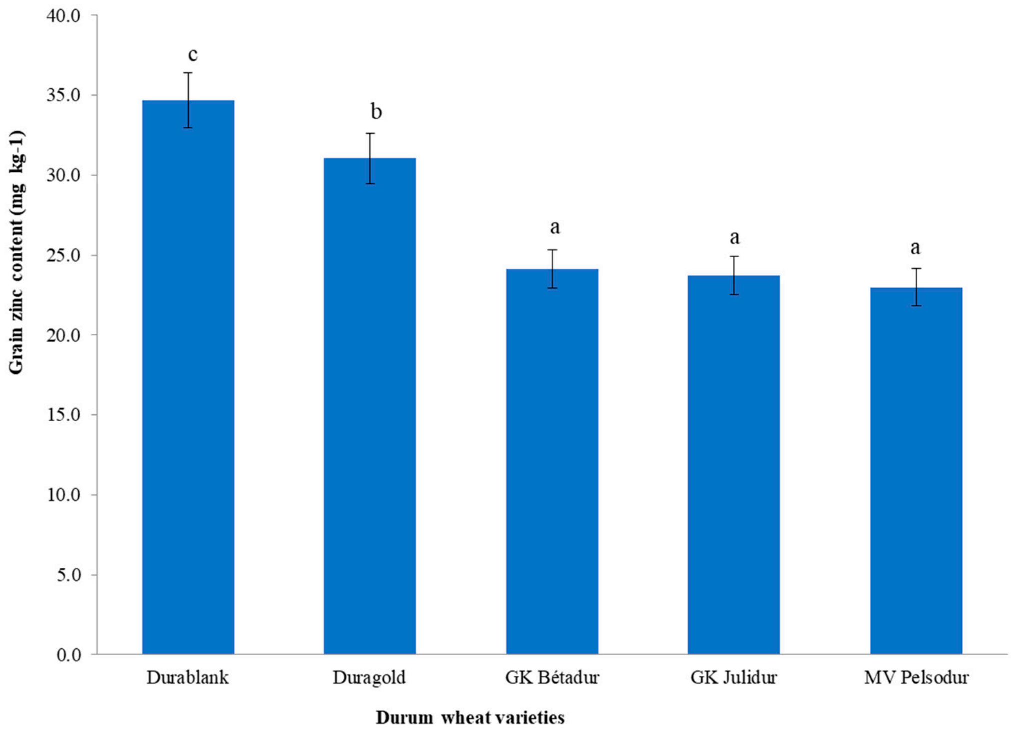


**Figure 5.** Effect of varieties on grain zinc concentration of durum wheat at Debrecen-Látókép, 2022–2023 cropping season. Values are means of three replicates ± standard error (SE). Bars labeled with different letters are significantly different at $p < 0.05$ (LSD test).

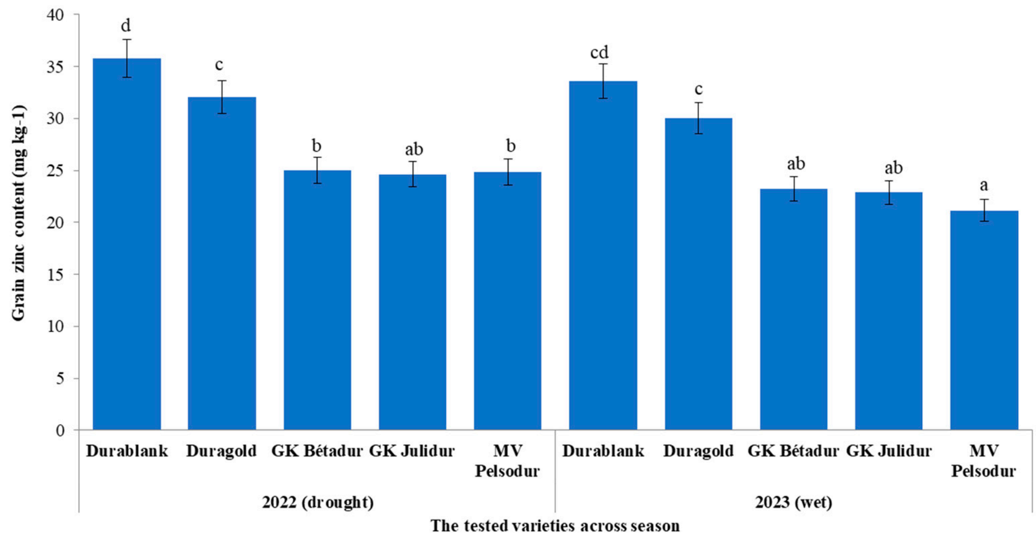


**Figure 6.** Interaction effect of durum wheat varieties and cropping seasons on grain zinc concentration at Debrecen-Látókép, 2022–2023 cropping season. Values are means of three replicates ± standard error (SE). Bars labeled with different letters are significantly different at $p < 0.05$ (LSD test), indicating that varieties performance for grain zinc varied between seasons.

Differences between spring- and winter-sown varieties were also evident. Spring-sown varieties, including Durablank and Duragold, consistently accumulated more zinc than winter-sown varieties ($p < 0.05$) (Figure 7). These findings demonstrate that both genetic potential and targeted agronomic interventions such as foliar zinc and sulfur application are important for optimizing grain zinc concentration. While varietal selection is critical, maximizing zinc content requires integrating varietal selection with appropriate nutrient management, especially under conditions of variable rainfall or soil zinc availability.

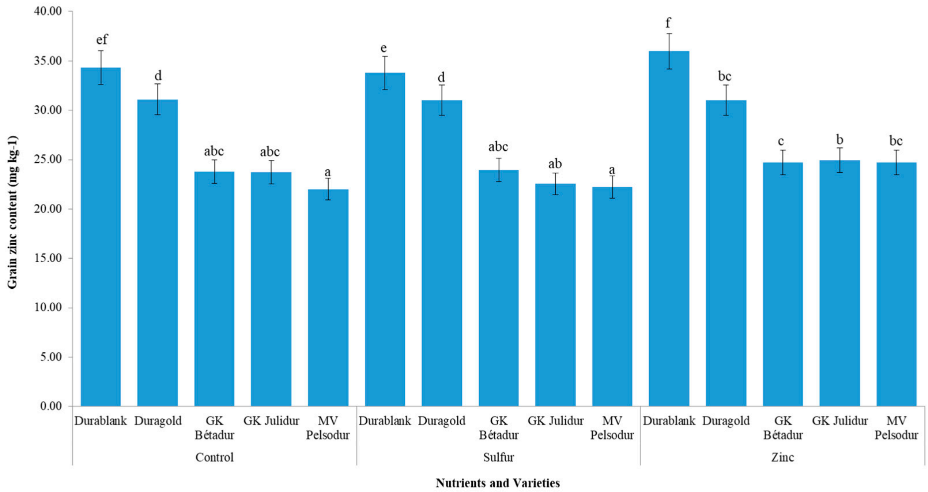


**Figure 7.** Effect of varieties on agronomic biofortification of durum wheat at Debrecen-Látókép, 2022–2023 cropping season. Values are means of three replicates ± standard error (SE). Bars labeled with different letters are significantly different at $p < 0.05$ (LSD test).

### 3.4. Nutrient Interrelationships in Durum Wheat Grain Composition

The correlation matrix illustrates the relationships among grain nutritional traits of durum wheat varieties cultivated during the 2022 and 2023 cropping seasons at Debrecen–Látókép. The color gradient, ranging from deep blue (−1.00) to deep red (+1.00), represents the strength and direction of correlations among 17 elements and grain protein content. Strong positive correlations were observed among several micronutrients, including Fe, Mn, Zn, and Cu, while negative correlations were noted between Na and certain macro- and micronutrients (Figure 8).

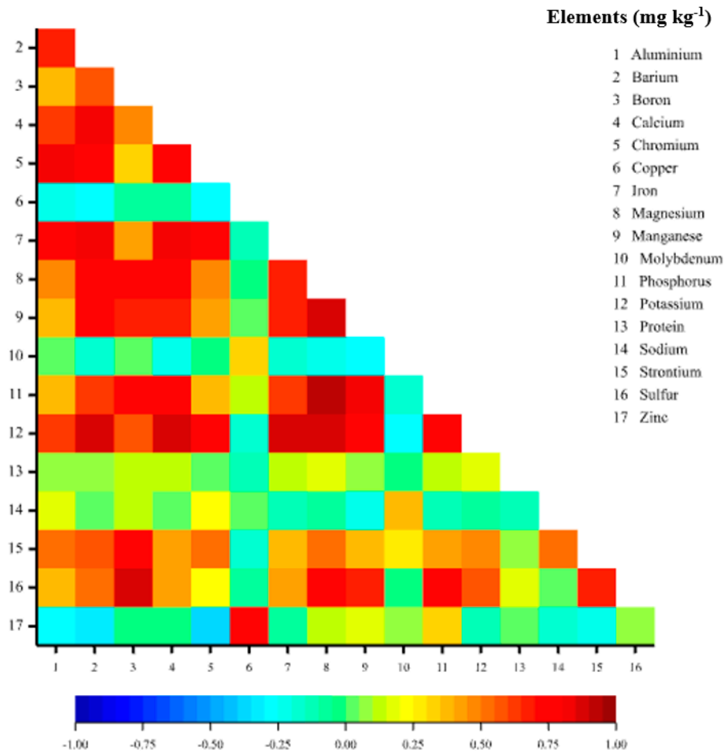


**Figure 8.** Pearson correlation matrix showing relationships among grain nutritional traits of durum wheat varieties grown at Debrecen−Látókép during the 2022 and 2023 cropping seasons. Values represent means pooled across both years, as varieties × year interactions were not statistically significant for the traits analyzed.

Correlation analysis revealed distinct clusters of positive and negative associations among grain nutrients. Strong positive correlations were observed among micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) ($p < 0.01$). Macronutrients such as phosphorus (P) and potassium (K) also displayed moderate to strong positive correlations with multiple elements, indicating potential co-regulation or shared uptake pathways. In contrast, negative correlations were detected between sodium (Na) and several transition metals, as well as between specific macro- and micronutrients (Figure 8).

## 4. Discussion

### 4.1. Genetic Variation in Grain Zinc and Protein Content

The pronounced variation in grain zinc accumulation among the studied durum wheat varieties indicates the dominant role of genetic factors in determining micronutrient content. Among the tested varieties, Durablank consistently accumulated the highest grain Zn levels, indicating its promise as a Zn-efficient varieties for biofortification efforts. The observed variation of ~50.87% among varieties suggests that breeding programmes have substantial scope to exploit genetic differences to elevate Zn content without necessarily compromising yield. This aligns with earlier reports showing varietal selection as a key determinant of micronutrient concentration in cereals [14]. In contrast, high-yielding winter-sown varieties such as MV Pelsodur and GK Julidur consistently exhibited lower zinc accumulation (Table 2). This pattern illustrates a tradeoff between yield potential and micronutrient density and reflects the complexity breeders face when simultaneously targeting high productivity and enhanced nutritional quality. Moreover, studies have shown that "Zn-efficiency" in wheat, the ability to maintain yield under low Zn availability involves specific biochemical or physiological traits rather than just root Zn uptake or translocation [15]. Grain protein content in this study likewise exhibited a clear trade-off with yield potential, consistent with the "dilution effect" often reported in cereals (meaning, when yield is high, nutrient concentration tends to decline). Varieties with high protein often had lower yields, whereas high-yielding varieties accumulated less protein. Varieties that strike an intermediate balance between protein, micronutrient density, and yield may represent valuable genetic resources for breeding programmes aimed at improving durum wheat quality for pasta, bread, and other bakery products [16].

### 4.2. Environmental Effects on Micronutrient Accumulation

Environmental conditions had a significant influence on zinc accumulation in grain. In our study, grain Zn concentrations were higher during the drought year (2022) compared with the wetter season (2023). One possible explanation is a stress-induced concentration effect: under water-limited conditions, reduced vegetative biomass may decrease the "dilution" of nutrients in the grain, potentially enhancing the efficiency of root-to-shoot nutrient allocation. Although physiological measurements were not conducted in this study, similar patterns have been reported in other cereals, where pre-harvest moisture stress can result in higher micronutrient concentrations despite lower overall yields [17]. Additionally, previous studies indicate that foliar Zn application combined with 6-BAP under drought conditions can improve grain Zn concentration and reduce the phytate-to-Zn molar ratio, suggesting improved Zn bioavailability under stress [18]. These observations highlight the importance of seasonal variation when designing biofortification and nutrient management strategies. Furthermore, the fact that varietal differences were more pronounced under stress conditions underscores the need for multi-season trials to accurately capture varietal performance under variable environmental conditions.

*4.3. Agronomic Interventions and Varietal-Specific Responses*

The result also indicates that foliar applications of Zn and S significantly enhanced grain Zn concentration, especially in Zn-efficient varieties such as Durablank. High-yielding varieties (MV Pelsodur) showed limited responsiveness, indicating that fertilizer strategies cannot be universally applied across varieties. In a comprehensive meta-analysis of agronomic Zn biofortification in wheat, soil applications increased grain Zn by ~29.1%, whereas foliar or combined soil + foliar applications increased grain Zn by ~55.2–62.3% [19]. The results also highlight varieties × fertility interactions, as nitrogen fertilization at 100 kg $ha^{-1}$ amplified the effects of foliar S and Zn on protein content and nutrient accumulation, suggesting that coordinated nutrient management can enhance grain nutritional quality. These observations are consistent with findings reported by Sangnak et al., [20] reinforcing the role of integrated fertilization strategies in optimizing nutrient-use efficiency. These interactions support the need for varietal-specific fertilization strategies rather than one-size-fits-all approaches.

The interaction among varieties, fertility, and environment further indicates the well-known tradeoff between yield and grain nutritional quality. High-yielding varieties often allocate more biomass to carbohydrate accumulation, diluting nutrient concentrations, whereas nutrient-efficient varieties may maintain higher nutritional quality under moderate inputs. In our trials, appropriate nutrient management allowed protein content to remain between ~14.3% and ~16.8% across tested varieties, indicating that well-designed fertilizer regimes can partially offset the negative effect of yield on protein accumulation and thereby meet functional requirements such as for pasta elasticity, cooking tolerance, water absorption.

*4.4. Implications for Human Nutrition and Durum Wheat Functionality*

Zinc deficiency is a major global health issue, and cereals including wheat contribute a large share of dietary calories in many populations. A study suggests that wheat grains providing grain Zn levels of ~40 mg $kg^{-1}$ are a realistic biofortification target [19]. In our study, Durablank consistently achieved Zn concentrations of ~33.5–35.3 mg $kg^{-1}$ depending on season, whereas MV Pelsodur and GK Julidur were below those thresholds. This suggests that varietal selection can meaningfully improve dietary Zn intake among populations dependent on wheat. Macro-minerals like calcium, magnesium, and potassium are essential for both human health [21] and crucial for determining the functionality and processing quality of different wheat varieties. The specific concentration and balance of these minerals, which differ among durum wheat varieties and are influenced by environmental factors and fertilization practices, require careful management to achieve desired outcomes in both nutritional value and processing performance. Varieties such as Durablank, Duragold and GK Julidur exhibited higher concentrations of these minerals, while MV Pelsodur accumulated lower levels. Thus, variety selection influences both nutritional and technological quality of durum wheat.

*4.5. Synergistic Nutrient Interactions and Biofortification Potential*

The strong positive correlations among Fe, Zn, Mn, and Cu observed in our study suggest coordinated uptake and regulation, likely through shared transport mechanisms or co-regulated genetic pathways. Similar trends have been reported in wheat, where under Zn-deficient conditions higher root Zn was associated with increased Fe while Cu and Mn responses varied with root-to-shoot translocation, whereas under Zn-sufficient conditions all micronutrients, including Zn, Fe, Cu, and Mn, exhibited synergistic interactions [22]. Our study found consistent positive correlations among phosphorus, potassium, and sulfur, indicating their synergistic roles in energy metabolism, enzyme activation, and protein synthesis. Previous studies support that deficiencies in these nutrients can disrupt metabolic pathways and reduce crop nutritional quality [23]. Sulfur's essential role in synthesizing amino acids such as cysteine and methionine, as well as glutathione, further highlights its influence on protein formation and redox regulation [24]. In contrast, the weak association between protein and mineral content in our data suggests that protein synthesis is primarily driven by nitrogen availability rather than direct mineral enrichment. These results provide a foundation for biofortification strategies that exploit synergistic relationships while minimizing negative nutrient tradeoffs during breeding and fertilization programmes.

### *4.6. Integrated Approach for Enhancing Durum Wheat Grain Quality*

The cumulative results point to the necessity of a holistic approach combining genetic selection, optimized nutrient management, and season-specific agronomy to enhance grain nutritional quality in durum wheat. Selecting Zn-efficient, spring-sown varieties such as Durablank in our study offers a promising pathway for achieving higher dietary micronutrient intake in regions with Zn-deficient soils. Adaptive management, that is, adjusting fertilization and sowing strategies in response to seasonal environment, can ensure stable grain quality across years. Adjusted fertilizer application that aligns varieties-specific uptake efficiency and root/system traits complement genetic potential. In effect, harnessing varietal differences, strategic fertilizer application, and multi-season evaluation allows simultaneous attainment of yield targets, improved micronutrient density, and enhanced food security in vulnerable agro-ecologies. This study demonstrates that varietal differences in Zn accumulation and nutrient efficiency, when combined with thoughtful agronomy (such as fertilizer choice and timing) and awareness of seasonal environmental variation, can achieve meaningful improvements in both nutritional and functional quality of durum wheat. This multi-factor framework is essential for sustainable biofortification programmes and aligns with emerging global evidence on micronutrient-dense durum wheat production.

The significant differences in protein content among durum wheat varieties demonstrate the strong influence of genetic factors on grain quality traits. The superior protein content observed in GK Julidur and GK Bétadur may indicate their higher genetic potential for nitrogen uptake, assimilation, and remobilization into the grain during the grain-filling period. Since protein content is a major determinant of semolina and pasta quality, these varieties are likely to be more suitable for high-quality end-use products. The moderate protein levels observed in Durablank, Duragold, MV Hundur, MV Pennedur, and MV Vékadur suggest stable performance but comparatively lower protein accumulation potential than the leading varieties. These differences may reflect variations in nitrogen-use efficiency, grain-filling duration, or sink–source relationships.

The comparatively low protein content of MV Pelsodur and Tamadur suggests either lower nitrogen-use efficiency or a stronger allocation of assimilates toward carbohydrate accumulation rather than protein synthesis. Lower grain protein concentration can negatively affect gluten strength and processing quality, particularly for pasta production where higher protein levels are preferred. The observed variation of approximately 1.5% is agronomically meaningful. In production systems where nitrogen availability is limited or fertilizer inputs are constrained, selecting varieties with inherently higher protein potential can improve grain quality without substantially increasing input costs. This is particularly relevant in environments where soil fertility management is challenging. The results universally highlight the importance of varietal selection as a practical and sustainable strategy for enhancing durum wheat grain quality, especially under varying soil fertility and nitrogen management conditions.

## 5. Conclusions

This study demonstrates that grain nutritional quality in durum wheat is strongly influenced by varieties × nutrient × environment interactions. The results indicate that spring durum wheat varieties exhibited greater capacity for micronutrient accumulation in grain compared with winter types, highlighting their potential for biofortification-oriented breeding and nutrient-dense wheat production. These findings suggest that varietal growth habits may play an important role in determining mineral accumulation patterns and should be considered in the development of climate-resilient and nutritionally improved durum wheat systems. Significant varietal differences were observed in macro- and micronutrient accumulation, with Durablank consistently exhibiting superior grain zinc concentration (34.70–35.79 mg $kg^{-1}$) compared with MV Pelsodur (23.0–24.8 mg $kg^{-1}$) and GK Julidur (23.8 mg $kg^{-1}$). Calcium, magnesium, and potassium also varied across varieties and seasons. Foliar zinc and sulfur applications enhanced grain zinc, particularly in zinc-efficient varieties, while nitrogen fertilization at 100 kg $ha^{-1}$ increased macronutrient accumulation by 12–20% relative to lower rates. Seasonal variation played a decisive role: drought in 2022 elevated grain zinc but limited potassium and magnesium, whereas favorable moisture in 2023 improved overall nutrient mobility and accumulation. A yield–protein trade-off was evident, with high-yielding varieties maintaining lower protein (~14%), while moderate-yield spring type varieties such as Durablank achieved up to 16.8%. These results highlight the importance of system-level, context-specific nutrient management to optimize both yield and grain nutritional quality in climate-resilient durum wheat production.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/seeds5020021/s1, Table S1. Interaction effect of nitrogen application rate, nutrient application, and genetic variation among durum wheat varieties on grain nutritional composition (mg $kg^{-1}$). Table S2. Nutritional composition (mg $kg^{-1}$) of durum wheat grain as influenced by the interaction effect between nitrogen rate and varietal difference. Table S3. Interaction effect of nitrogen and growing season on nutritional composition of durum wheat grains.

**Author Contributions:** Conceptualization, A.A.M. and É.B.Á.; methodology, A.A.M.; software, A.A.M.; validation, A.A.M. and É.B.Á.; formal analysis, A.A.M.; investigation, A.A.M. and É.B.Á.; resources, G.G.C. and É.B.Á.; data curation, A.A.M.; writing—original draft preparation, G.G.C., A.A.B. and É.B.Á.; writing—review and editing, G.G.C., A.A.M. and É.B.Á.; visualization, A.A.M., É.B.Á., G.G.C. and A.A.B.; supervision, É.B.Á.; project administration, A.A.M. and É.B.Á.; funding acquisition, É.B.Á. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Tempus Public Foundation and the University of Debrecen, Hungary.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to institutional and research project restrictions.

**Acknowledgments:** We would like to express our gratitude to all Látókép research site stuff for their technical guidance throughout the experimental period. We also highly appreciated the funding support from the Tempus Public Foundation within the framework of the Stipendium Hungaricum Scholarship Programme, supported by Ministry of Education (MoE, https://moe.gov.et/ accessed date: 29 March 2025) of Ethiopia and Debark University (https://dku.edu.et/ accessed date: 29 March 2025).

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

## References

1. Beres, B.L.; Rahmani, E.; Clarke, J.M.; Grassini, P.; Pozniak, C.J.; Geddes, C.M.; Porker, K.D.; May, W.E.; Ransom, J.K. A Systematic Review of Durum Wheat: Enhancing Production Systems by Exploring Genotype, Environment, and Management (G × E × M) Synergies. *Front. Plant Sci.* **2020**, *11*, 568657. [CrossRef]
2. Zingale, S.; Spina, A.; Ingrao, C.; Fallico, B.; Timpanaro, G.; Anastasi, U.; Guarnaccia, P. Factors Affecting the Nutritional, Health, and Technological Quality of Durum Wheat for Pasta-Making: A Systematic Literature Review. *Plants* **2023**, *12*, 530. [CrossRef]
3. Ali, A.A.H. Overview of the vital roles of macro minerals in the human body. *J. Trace Elem. Miner.* **2023**, *4*, 100076. [CrossRef]
4. Zhu, H.; Mao, S.; Li, W. Association between Cu/Zn/Iron/Ca/Mg levels and cerebral palsy: A pooled-analysis. *Sci. Rep.* **2023**, *13*, 18427. [CrossRef]
5. Ram, H.; Naeem, A.; Rashid, A.; Kaur, C.; Ashraf, M.Y.; Malik, S.S.; Aslam, M.; Mavi, G.S.; Tutus, Y.; Yazici, M.A.; et al. Agronomic biofortification of genetically biofortified wheat genotypes with zinc, selenium, iodine, and iron under field conditions. *Front. Plant Sci.* **2024**, *15*, 1455901. [CrossRef]
6. Hernandez-Espinosa, N.; Laddomada, B.; Payne, T.; Huerta-Espino, J.; Govindan, V.; Ammar, K.; Ibba, M.I.; Pasqualone, A.; Guzman, C. Nutritional quality characterization of a set of durum wheat landraces from Iran and Mexico. *LWT* **2020**, *124*, 109198. [CrossRef]
7. Barunawati, N.; Hettwer Giehl, R.F.; Bauer, B. The influence of inorganic nitrogen fertilizer forms on micronutrient retranslocation and accumulation in grains of winter wheat. *Front. Plant Sci.* **2013**, *4*, 320. [CrossRef]
8. Wysocka, K.; Cacak-Pietrzak, G.; Sosulski, T. Mineral Concentration in Spring Wheat Grain Under Organic, Integrated, and Conventional Farming Systems and Their Alterations During Processing. *Plants* **2025**, *14*, 1003. [CrossRef]
9. Wan, C.; Dang, P.; Gao, L.; Wang, J.; Tao, J.; Qin, X.; Feng, B.; Gao, J. How Does the Environment Affect Wheat Yield and Protein Content Response to Drought? A Meta-Analysis. *Front. Plant Sci.* **2022**, *13*, 896985. [CrossRef]
10. Melash, A.A.; Bogale, A.A.; Bytyqi, B.; Nyandi, M.S.; Ábrahám, É.B. Nutrient management: As a panacea to improve the caryopsis quality and yield potential of durum wheat (*Triticum turgidum* L.) under the changing climatic conditions. *Front. Plant Sci.* **2023**, *14*, 1232675. [CrossRef]
11. Csajbók, J.; Pepó, P.; Kutasy, E. Photosynthetic and Agronomic Traits of Winter Barley (*Hordeum vulgare* L.) Varieties. *Agronomy* **2020**, *10*, 1999. [CrossRef]
12. Payne, R.; Murray, D.; Harding, S.; Baird, D.; Soutar, D. *Introduction to Genstat for Windows*, 18th ed.; VSN International: Hertfordshire, UK, 2015; pp. 1–144. Available online: https://vsni.co.uk/software/genstat/ (accessed on 21 December 2025).
13. Evans, J.D. *Straightforward Statistics for the Behavioral Sciences*; Thomson Brooks/Cole Publishing Co.: Belmont, CA, USA, 1996.
14. Chattha, M.U.; Hassan, M.U.; Khan, I.; Chattha, M.B.; Mahmood, A.; Chattha, M.U.; Nawaz, M.; Subhani, M.N.; Kharal, M.; Khan, S. Biofortification of Wheat Cultivars to Combat Zinc Deficiency. *Front. Plant Sci.* **2017**, *8*, 281. [CrossRef]
15. Hacisalihoglu, G.; Hart, J.J.; Wang, Y.H.; Cakmak, I.; Kochian, L.V. Zinc efficiency is correlated with enhanced expression and activity of zinc-requiring enzymes in wheat. *Plant Physiol.* **2003**, *131*, 595–602. [CrossRef] [PubMed]
16. Melash, A.A.; Ábrahám, É.B. Barriers and levers to enhance end-use functional properties of durum wheat (*Triticum turgidum* L.) grain: An agronomic implication. *Heliyon* **2022**, *8*, e09542. [CrossRef]
17. Farahbakhsh, H.; Khasse Sırjanı, A. Enrichment of Wheat by Zinc Fertilizer, Mycorrhiza and Preharvest Drought Stress. *Turk. J. Field Crops* **2019**, *24*, 1–6. [CrossRef]
18. Zarea, M.J.; Karimi, N. Grain yield and quality of wheat are improved through post-flowering foliar application of zinc and 6-benzylaminopurine under water deficit condition. *Front. Plant Sci.* **2023**, *13*, 1068649. [CrossRef]
19. Hui, X.; Luo, L.; Chen, Y.; Palta, J.A.; Wang, Z. Zinc agronomic biofortification in wheat and its drivers: A global meta-analysis. *Nat. Commun.* **2025**, *16*, 3913. [CrossRef]
20. Sangnak, S.; Veeradittakit, J.; Prom-u-thai, C. Comparative impacts of nitrogen, sulfur, and zinc fertilization on grain yield, protein content, antioxidant capacity and its loss during polishing process among rice varieties. *Front. Agron.* **2026**, *7*, 1725441. [CrossRef]
21. Razzaque, M.S.; Wimalawansa, S.J. Minerals and Human Health: From Deficiency to Toxicity. *Nutrients* **2025**, *17*, 454. [CrossRef]
22. Niazkhani, M.; Navvabi, A. Interactions between Zn, Fe, Cu and Mn in Various Organs of Bread Wheat at Deficiency and Adequate of Absorbable Zinc. *Am. J. Plant Sci.* **2025**, *16*, 232–244. [CrossRef]
23. Amtmann, A.; Armengaud, P. Effects of N, P, K and S on metabolism: New knowledge gained from multi-level analysis. *Curr. Opin. Plant Biol.* **2009**, *12*, 275–283. [CrossRef] [PubMed]
24. Donnay, N.; Couturier, J.; Rouhier, N. Redox regulation of enzymes involved in sulfate assimilation and in the synthesis of sulfur-containing amino acids and glutathione in plants. *Front. Plant Sci.* **2022**, *13*, 958490. [CrossRef]