Theses of Doctoral (PhD) Dissertation

INFLUENCE OF NUTRIENT SUPPLY AND DROUGHT STRESS ON GROWTH, YIELD AND GRAIN QUALITATIVE TRAITS OF DURUM WHEAT (Triticum turgidum L.) VARIETIES

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1. Introduction

1.1. Rationale and Context

Durum wheat (Triticum turgidum var. durum, 2n = 28, AABB) is a widely cultivated free-threshing allotetraploid wheat, contributing approximately 5% of global wheat (Triticum spp.) production. Valued for its unique storage proteins, it serves as the primary raw material for pasta, couscous, and certain types of bread. However, only 13% of the world's arable land is suitable for durum wheat cultivation. Alarmingly, climate change is predicted to reduce this suitable area by 19% by the mid-century and by 48% by its end. These environmental challenges, coupled with rising global food demands, pose significant threats to the yield stability and nutritional value of durum wheat. These threat requires innovative agronomic solutions to balance the need for increased production with the environmental realities of modern agriculture.

Improving the grain yield and commercial value of durum wheat involves enhancing nitrogen use efficiency (NUE), managing genetic variability, understanding genotype-environment interactions, and adapting cultivation practices to diverse conditions. Strategies to improve grain protein content and yield typically focus on optimizing nitrogen uptake or increasing nitrogen doses. However, the relationship between high nitrogen application rates and yield improvements remains inconsistent. While some studies show significant yield increases with higher nitrogen levels, others report declines in yield and protein content, depending on variety and growing season. These discrepancies reflect complex interactions among genetic traits, environmental factors, and management practices. A targeted, multifactorial approach to nitrogen management that accounts for varietal and environmental differences is crucial. Leveraging precision agriculture tools can help optimize NUE, aligning nitrogen applications with crop and environmental needs to balance productivity and quality.

Nitrogen fertilization plays a critical role in crop productivity, yet its effectiveness varies significantly across climatic conditions. Moisture availability is a key factor modulating the impact of nitrogen application on crop performance. During wet seasons, excessive nitrogen application often leads to reduced grain yield, NUE, and flour quality. It promotes excessive vegetative growth, increasing the risk of lodging and resulting in suboptimal allocation of resources for reproductive development. Conversely, under dry conditions, high nitrogen levels accelerate vegetative growth at the expense of reproductive processes, culminating in a phenomenon known as "haying off." This premature drying and senescence of plant tissues exacerbate water stress, leading to reduced grain yield, fewer grains per spike, and diminished nutritional quality, particularly under terminal drought conditions. This complex interaction between nitrogen application, moisture availability, and crop physiology indicates the need for strategic nitrogen management specific to environmental conditions.

Integrated agronomic strategies are indispensable for addressing both productivity and sustainability challenges in durum wheat cultivation. Sulfur and zinc, when applied exogenously or in combination with nitrogen, have shown considerable potential in enhancing nitrogen use efficiency, grain yield, and protein content. Sulfur, in particular, plays a crucial role in mitigating growth constraints in water-limited environments. Under drought conditions, reduced SO_4^{2-} availability hinders nitrate NO_3^- uptake due to decreased CO_2 fixation and diminished sulfur flux into cysteine, a critical amino acid for plant metabolism. This limitation prevents wheat from achieving its yield potential and compromises nutrient utilization efficiency. The synergistic relationship between nitrogen and sulfur in protein synthesis further highlights the importance of balanced nutrient management. Deficiencies in one nutrient exacerbate the other's limitation, leading to compounded negative effects on growth and productivity. Research demonstrates that sulfur deficiency can impair nitrogen use efficiency, while nitrogen deficiency reduces sulfur utilization efficiency, emphasizing the need for an optimal nitrogen-to-sulfur ratio to maximize yields and grain quality.

Zinc, alongside sulfur, plays a critical role in mitigating the negative effects of high nitrogen application, irrespective of seasonal moisture conditions. Zinc enhances nutrient uptake, regulates key metabolic processes, reduces oxidative stress, and supports root development, thereby improving drought tolerance and nutrient balance. It also strengthens physiological and molecular mechanisms essential for stress resilience, reducing the risk of "haying off" and promoting reproductive growth, which ultimately improves grain yield and quality under adverse environmental conditions. The combined application of sulfur and zinc optimizes resource allocation toward reproductive development, enhancing crop performance under drought and other environmental stressors. These nutrient management strategies offer sustainable solutions to address nutrient imbalances, improve nitrogen use efficiency, and strengthen durum wheat’s resilience to environmental challenges, contributing to food security while reducing agriculture’s environmental impact. This study seeks to advance the discourse on sustainable agriculture by examining the synergistic effects of nutrient management and environmental adaptation in durum wheat production. It specifically addresses climate-induced challenges by integrating targeted nutrient strategies, such as nitrogen rate, sulfur and zinc applications, with varietal adaptability to optimize yield, enhance nitrogen use efficiency, and improve grain quality across diverse environmental conditions.

a) Assess the yield, agronomic characteristics, commercial qualitative traits, and physiological responses of diverse durum wheat varieties under the influence of seasonal and intra-varietal variations.
a) Evaluate the effects of foliarly applied zinc and sulfur fertilizers, as well as soil-based nitrogen application rates, on stand establishment, grain yield, physiological traits, and the nutritional composition of durum wheat.
b) Investigate agronomic biofortification strategies for enhancing grain mineral concentration, protein content, and overall yield in durum wheat varieties.
c) Examine the relationships between storage grain protein composition and grain yield in durum wheat, considering genetic variability and environmental influences.
d) Analyze the effects of terminal drought stress on agronomic, phenological, physiological, and grain qualitative traits in various durum wheat varieties.

2. Material and Methods

2.1. Descriptions of the Study Area

The evaluation of nine plant materials carried out during the spring season at the Látókép research center of the University of Debrecen, Hungary, located at 47°33042″ N; 21°27002″ E, approximately 15 km from Debrecen. This site features calcareous chernozem soil with around 2.7–2.8% humus, nearly neutral pH (pH KCl = 6.46), and a specific plasticity index (K_A) of 40. Soil analysis indicated values of approximately 57 mg kg^{-1} AL-soluble phosphorus, 199 mg kg^{-1} AL-soluble potassium, and 0.94 mg kg^{-1} of zinc. To analyses soil nutrient status, the soil samples were collected from 0–20 cm at various locations before nutrient application in the experimental plots. The soil's water management characteristics were favorable. However, the soil moisture content at the experiment site predominantly relied on annual precipitation during the entire experimentation period.

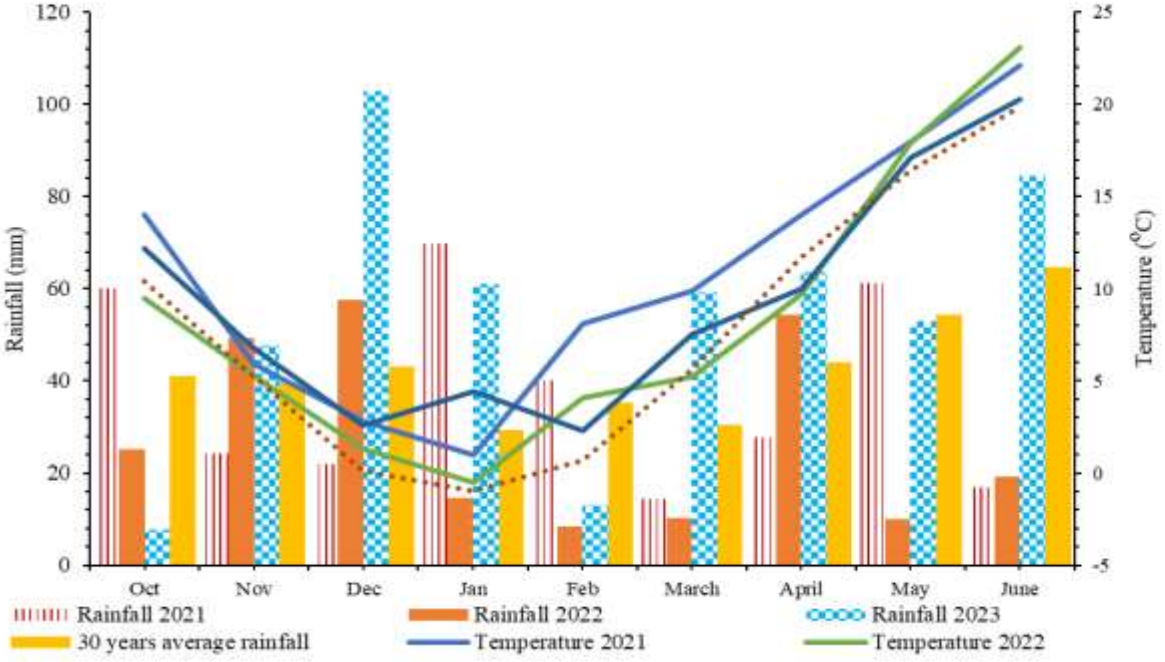


Figure 1. Illustrates the average daily meteorological data—precipitation, and temperature—recorded at the Látókép experimental site throughout the 2021–2023 cropping seasons, providing a comparative analysis against meteorological data spanning 30 years.

The climate data for 2021, 2022, and 2023 showed significant variability in rainfall and temperature, impacting crop production. In 2021, a dry year with low rainfall in key months, such as March and April, resulted in drought conditions and limited crop growth. Although 2022 also experienced drought, it was less severe, with some months like November receiving above-average rainfall. In contrast, 2023 was wetter, with above-average rainfall in critical months like December, March, and June, providing favorable conditions for crop growth. Temperature trends followed similar patterns, with 2021 experiencing higher-than-average temperatures exacerbating dry conditions, while 2022 and 2023 saw more variability, with 2023 benefiting from warmer temperatures and abundant rainfall, promoting optimal growth (Figure 1).

2.2. Experimental Design and Treatments

The experiment was conducted using a multi-factorial split-split plot design with three replications to assess the effects of nitrogen application rates, durum wheat varieties, and foliar fertilizer treatments. The main plots were allocated to two nitrogen levels (60 and 100 kg ha^{-1}), while the subplots were assigned to ten durum wheat varieties, and the sub-sub plots were designated for three foliar fertilizer treatments (Control, Zinc, and Sulfur). Each experimental unit measured 13.5 m^2 (9 m × 1.5 m) with a row spacing of 15 cm. Foliar fertilizers were applied at the critical flag leaf stage, with sulfur at a rate of 4 L ha^{-1} and zinc at 3 L ha^{-1}. These rates were consistently maintained across all experimental units and cropping years. Standard agronomic practices, including pest and disease management, were uniformly implemented across the study, adhering to established guidelines for durum wheat cultivation.

2.3. Data Collection

A Minolta SPAD-502 chlorophyll meter was employed to measure the relative leaf chlorophyll concentration and nitrogen status of durum wheat at different growth stages, from early tillering to early maturity, in both spring and winter growing seasons. The SPAD meter works by measuring leaf transmittance at two specific wavelengths: 650 nm, where chlorophyll absorbs light, and 940 nm, representing near-infrared light that is not absorbed by chlorophyll. These readings provide a non-destructive method for estimating leaf chlorophyll content and, by extension, nitrogen status. LAI was determined using the Delta-T SunScan SS1 Canopy Analysis System, which measures light transmission and assesses incident and transmitted Photosynthetically Active Radiation (PAR) within crop canopies. The system features a 100 cm probe with 64 PAR sensors covering the 400 to 700 nm spectral range. Readings were expressed in terms of PAR quantum flux (μmol

$m^{-2} s^{-1}$) and correlated with LAI ($m^2 m^{-2}$), providing detailed information on crop canopy structure, which is essential for evaluating crop health and productivity.

Grain yield was measured after harvesting a 13.5 m^2 area (1.5 × 9 m) using a Sampo Rosenlew SR 2010 plot combine equipped with a Coleman weighing system. Yield was calculated in kilograms per hectare (kg ha^{-1}), and the harvested grain was standardized to a moisture content of 12.5%. Growth and yield attributes were systematically recorded from five plants per biological replicate in each technical replicate, including spike length, plant height, and awn length. Spike length was measured from the base to the apex (excluding awns), and plant height was recorded from the soil surface to the top of the spike. Spike density was determined by counting productive spikes within a 1×1-meter quadrant, offering insights into reproductive efficiency. Grain protein and moisture content were analysed using the Pfeuffer Granolyser NIR, which utilizes Near Infrared (NIR) diode technology to perform 1500 individual scans per sample, providing accurate assessments of grain composition. Grain mineral concentration was quantified using a PerkinElmer Optima 3300 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), capable of detecting multiple elemental concentrations simultaneously. This detailed and precise methodology ensured accurate evaluation of growth, yield, and grain quality parameters across the experimental treatments.

2.4. Statistical Data Analysis

The presented results are expressed as mean values, and the error bars depicted on the graphs represent the standard error (SE) of the difference of means. All collected data underwent statistical analysis using the GenStat (18th ed.) statistical software package. Prior to statistical assessments, normality and homogeneity of data were verified using the Shapiro–Wilk test. The majority of plant based parameters and yield metrics demonstrated normal distribution, and subsequent statistical analysis of the experimental data was conducted through analysis of variance (ANOVA). When the ANOVA indicated a significant difference, the mean values of treatment groups were compared using the least significant difference (LSD) t-test ($p\text{-value} \leq 0.05$) to discern differences in the expression levels of nutrients under drought-stressed plants. Additionally, Pearson's correlation coefficient was utilized to illustrate associations between pairs of measured traits. The mean values were employed to construct the graphs using the graphing features in MS Excel.

3. Results and Discussion

3.1. Varietal Response to Limited Nitrogen Supply in Durum Wheat

During the 2021 cropping season, the tested durum wheat varieties were evaluated under two nitrogen application scenarios: 60 kg ha^{-1} of nitrogen and no nitrogen application. Among the spring-sown varieties, Duragold (7468 kg ha^{-1}), Durablank (6901 kg ha^{-1}), and Colliodur (6702 kg ha^{-1}) displayed a notable positive yield response to nitrogen fertilization at 60 kg ha^{-1}, emphasizing their ability to effectively utilize additional nitrogen for increased productivity (Figure 2). These results reinforce the notion that spring-sown varieties benefit significantly from nitrogen inputs, particularly in terms of yield enhancement. Tamadur, in particular, demonstrated a pronounced sensitivity to nitrogen fertilization. Under unfertilized conditions, it produced a low yield of 4014 kg ha^{-1}, but when treated with 60 kg ha^{-1} of nitrogen, its grain yield surged by 46.81%, reaching 5893 kg ha^{-1}. This remarkable increase highlights Tamadur's dependency on adequate nitrogen inputs for optimal performance. The comparatively lower yields of spring-sown varieties, such as Duragold and Durablank, reflect their reduced drought tolerance, possibly due to shorter growth cycles that limit root development and water uptake. The drought sensitivity observed in Tamadur highlights its vulnerability to water stress, emphasizing the need for careful consideration of varietal selection under such conditions.

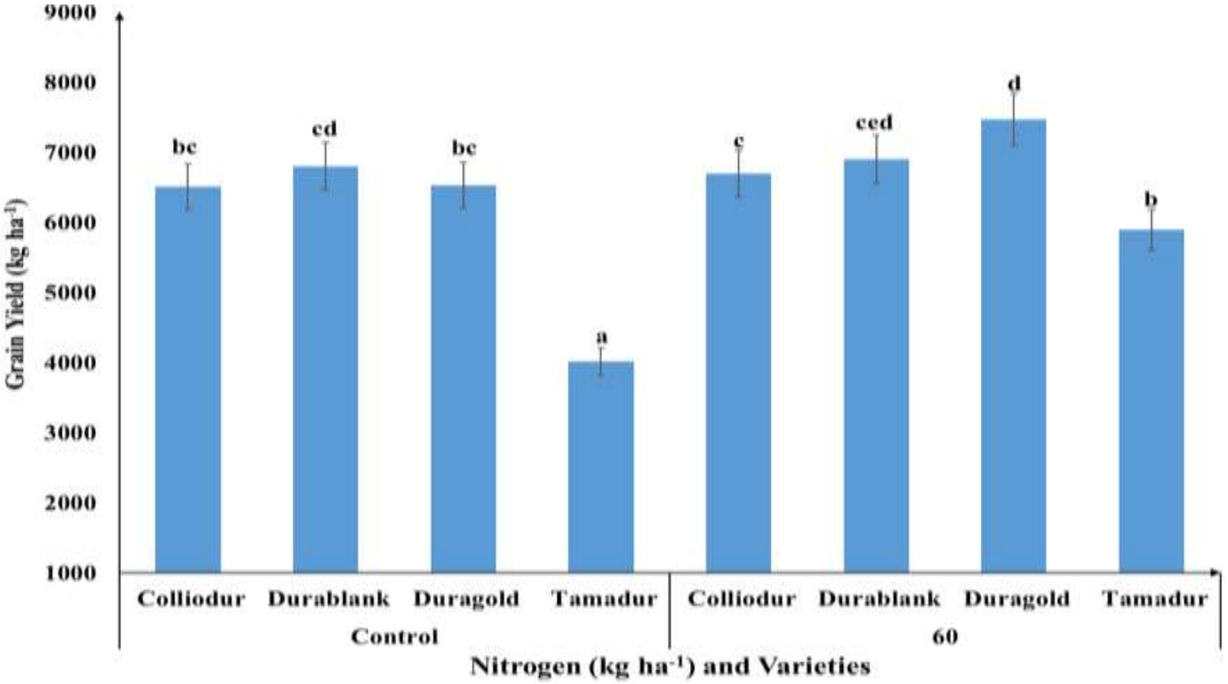


Figure 2. Yield performance of durum wheat varieties with and without nitrogen fertilization under drought conditions during the 2021 cropping season

In contrast, the winter-sown varieties showed no significant yield response to nitrogen treatment. This lack of response could be attributed to their genetic traits, which likely enable them to maintain stable yields even under low-fertilizer conditions, reflecting their adaptability to resource-limited environments. However, the main effect of durum wheat varieties on grain yield was significant in the 2021 cropping season. This indicates the critical role of genetic traits in determining yield performance under water-limited conditions. However, Tamadur proved to be particularly drought-sensitive, exhibiting a substantial reduction in grain yield during the challenging growing season. These findings emphasize the importance of genetic selection in mitigating the adverse effects of drought on durum wheat production.

3.2. Varietal Response to Nitrogen Levels in Durum Wheat

Nitrogen fertilizer application revealed significant genetic variability ($p < 0.001$) among durum wheat varieties. MV Pelsodur achieved the highest grain yield (7501 kg ha^{-1}), outperforming MV Hundur (6510 kg ha^{-1}) and Tamadur (4248 kg ha^{-1}) under the lowest nitrogen rate. The 43.4% yield difference between MV Pelsodur and Tamadur highlights the genetic predisposition of MV Pelsodur for higher productivity under limited nitrogen. Notably, MV Pelsodur maintained high yields across nitrogen levels, producing 7501 kg ha^{-1} at 60 kg ha^{-1} and 7439 kg ha^{-1} at 100 kg ha^{-1}, reflecting its adaptability to variable nitrogen conditions (Table 1). This adaptability is crucial in agricultural settings where nitrogen availability fluctuates due to factors such as soil properties, environmental conditions, and agronomic management practices.

Varietal differences in response to nitrogen levels showed clear distinctions between spring- and winter-planted durum wheat. Increasing nitrogen rates from 60 to 100 kg ha^{-1} significantly improved grain yields in spring varieties, with Durablank and Tamadur showing increases of 9.10% and 30.48%, respectively. In contrast, winter varieties experienced yield reductions, with GK Julidur and GK Bétadur showing decreases of 12.27% and 18.18%, respectively. These results highlight the need for season-specific nitrogen management, as spring varieties thrived under higher nitrogen, while winter varieties were negatively affected (Figure 2).

While genetic variation influenced nitrogen response, cropping season had an even greater impact. A significant interaction ($p < 0.001$) between nitrogen rates, varietal traits, and cropping season dynamics shaped nitrogen requirements and grain yield. Spring-sown varieties consistently benefited from a nitrogen rate of 100 kg ha^{-1}, achieving an 11.17% yield increase in the adequately moist 2023 season and up to a 21.11% increase in the drier 2022 season (Figure 3). This indicates the effectiveness of nitrogen fertilization in optimizing productivity for spring varieties across varying moisture conditions. In contrast, the response of winter varieties to the same nitrogen rate was less consistent and highly dependent on seasonal moisture levels. These results emphasize the importance of tailoring nitrogen management strategies to both cropping season and varietal characteristics to maximize durum wheat productivity.

Table 1. The interaction effect analysis between durum wheat varieties and nitrogen levels, as well as between cropping years and nitrogen levels, concerning yield, and associated yield metrics.

N rate (kg ha^{-1})	**Varieties**	**PH (cm)**	**AWL (Cm)**	**SPL (Cm)**	**SPP (m^2)**	**GPC (%)**	**GY (kg ha^{-1})**
60	GK Bétadur	75.96	9.66	6.81	525.30	15.33	5704.13
	GK Julidur	73.51	10.17	5.84	506.40	15.12	6349.78
	MV Hundur	86.76	8.00	6.76	499.30	14.90	6510.22
	MV Pelsodur	83.59	9.84	7.47	460.00	14.46	7500.72
	MV Pennedur	84.89	8.33	5.98	507.30	15.11	6386.09
	MV Vékadur	87.07	10.32	7.07	511.60	14.43	6456.74
	Durablank	69.09	9.10	4.46	341.60	15.80	4592.09
	Duragolg	69.16	8.76	4.65	348.00	15.09	5090.03
	Tamadur	69.04	8.96	4.53	371.30	14.57	4248.03
100	GK Bétadur	78.58	8.82	6.36	484.90	15.84	4667.12
	GK Julidur	74.62	9.67	5.78	526.90	16.54	5570.78
	MV Hundur	88.11	7.61	6.78	501.60	15.82	6098.42
	MV Pelsodur	86.40	9.09	7.72	479.60	14.18	7438.99
	MV Pennedur	86.51	8.41	6.24	518.70	15.02	6447.23
	MV Vékadur	86.56	10.24	7.12	550.90	15.71	6402.80
	Durablank	70.67	7.70	6.47	369.80	15.36	5011.71
	Duragolg	71.51	7.95	6.28	382.40	15.67	5529.38
	Tamadur	70.76	7.78	6.56	391.30	15.03	5542.78
LSD $_{0.05}$		5.60	1.63	0.69	32.97	1.02	395.77
CV (%)		4.5	11.4	6.9	3.1	3.50	2.90

In the 2023 cropping season, which had adequate moisture, the application of 100 kg ha^{-1} nitrogen led to a 7.42% reduction in productivity for winter-sown varieties (Figure 3). This decrease highlights the sensitivity of winter-type durum wheat to excessive nitrogen under favorable moisture conditions, likely due to imbalanced growth and increased susceptibility to lodging. On the other hand, in the drier 2022 season, the negative impact of excessive nitrogen was mitigated, but grain yield still decreased by 3.66%, demonstrating the variability in nitrogen response across different durum wheat varieties. These observations highlight the necessity for precise nitrogen management, especially in winter-type varieties, where responses can be highly dependent on both nitrogen levels and environmental conditions.

As nitrogen application rates increase from adequate (60 kg ha^{-1}) to excessive (100 kg ha^{-1}), a diminishing or even negative impact on yield, particularly during wet seasons, becomes evident. Grain yield was consistently higher in the wet cropping season compared to the dry season. However, a 2.52% yield decline was observed when nitrogen rates were doubled, highlighting the diminishing returns associated with excessive nitrogen application. In contrast, during the dry season, doubling nitrogen resulted in a 2.31% yield increase, suggesting that under water-limited conditions, durum wheat is more constrained by water availability than nutrients. In such conditions, additional nitrogen improves nutrient access and efficiency, leading to a higher grain yield.

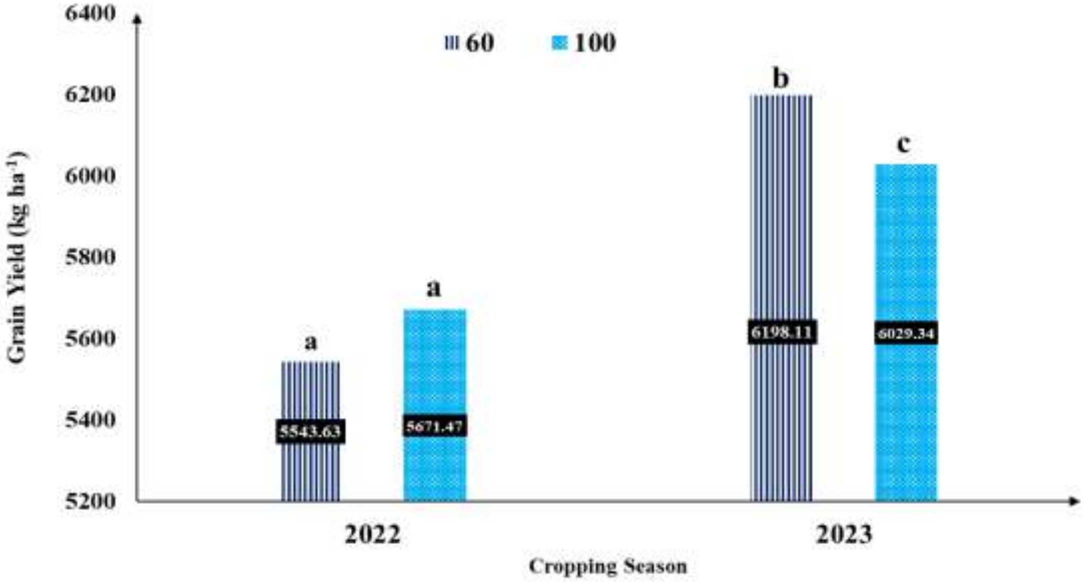


Figure 3. Impact of seasonal variation on nitrogen application rate and its effect on yield. Bars labelled with the same letter indicate no statistical difference, while bars with different letters are statistically significant.

Analysis of variance ($p < 0.001$) revealed a significant interaction between growing season and nitrogen application rates on grain yield (Figure 3). While the highest grain yield (6198.11 kg ha^{-1}) was recorded at the lowest nitrogen rate of 60 kg ha^{-1}, nitrogen's effect varied considerably between the two growing seasons (Figure 3). In 2023, a year marked by adequate rainfall and temperature stability, nitrogen had a more pronounced effect on grain yield than in 2022 (Figure 3), a drier season characterized by fluctuating temperature and irregular rainfall distribution. These findings suggest that nitrogen's impact on durum wheat is not only influenced by the nitrogen level itself but also by the climatic conditions of the growing season.

The interaction between variety, nutrient application, and growing season significantly ($p < 0.05$) influenced grain yield (Table 2). In 2023, MV Pelsodur achieved the highest yield for winter-sown varieties with sulphur (8558.22 kg ha^{-1}) and zinc (8464.74 kg ha^{-1}), suggesting that these nutrients enhanced stress tolerance under favorable conditions (Table 2). In contrast, during the 2022 season, MV Vékadur yielded 7540.24 kg ha^{-1} with sulphur, while zinc resulted in 6970.35 kg ha^{-1}, highlighting the different nutrient responses based on environmental conditions. Among spring-sown varieties, Duragold achieved the highest yield (6319.18 kg ha^{-1}) with sulphur in 2023, while Tamadur's yield was significantly lower in 2022 (3932.02 kg ha^{-1}), improving by 58.3% in 2023. The increased yield for Duragold suggests that sulphur was particularly beneficial in 2023, whereas Tamadur's poor performance in 2022 indicates that other factors, beyond sulphur, affected its yield. These results imply the importance of season-specific nutrient management strategies.

Table 2. A combined effect of foliarly applied nutrients, cropping year and genetic landscape on grain yield formation of durum wheat varieties

Varieties	**Control**		**Sulphur**		**Zinc**	
	2022	**2023**	**2022**	**2023**	**2022**	**2023**
GK Bétadur	4977.87	6199.43	5748.18	4580.70	4448.72	5158.85
GK Julidur	5780.91	5922.26	6746.28	6401.76	5465.88	5444.56
MV Hundur	5569.05	6373.42	6659.81	6729.09	6265.79	6062.09
MV Pelsodur	6014.08	7986.48	7089.28	8558.22	6706.33	8464.74
MV Pennedur	5850.83	6777.47	7062.66	5870.13	6393.71	6545.15
MV Vékadur	6252.21	6082.10	7540.24	5938.49	6970.35	5795.22
Durablank	4325.52	4678.74	4628.22	5179.03	4915.41	5084.48
Duragold	4456.57	5721.80	4813.82	6319.18	4697.23	5849.63
Tamadur	4120.92	5306.61	3932.02	6224.19	3971.92	5816.78
LSD $_{0.05}$	589.113	589.113	589.113	589.113	589.113	589.113
CV (%)	5.8	5.8	5.8	5.8	5.8	5.8

When sulfur-containing fertilizers were combined with a high nitrogen rate of 100 kg ha^{-1}, a significant ($p < 0.001$) 14.42% increase in grain yield was observed (Figure 3). This highlights the potential of sulfur to mitigate the negative effects of excessive nitrogen and enhance its beneficial impact on yield. Although nitrogen alone at the lowest rate resulted in the highest yield, combining nitrogen with zinc led to a 10% yield increase (5539.78 kg ha^{-1}), and the addition of sulfur further increased this to 15% (6338.54 kg ha^{-1}, Figure 4). However, applying high nitrogen alone did not significantly impact yield compared to sulfur alone, which resulted in 5790.19 kg ha^{-1}, showing only a minimal 1.13% variation (Table 6). In contrast, the combination of nitrogen and sulfur produced a substantial yield increase ranging from 8.24% to 9.48%, indicating a clear synergistic effect (Figure 4). This synergy suggests that co-fertilization with both nitrogen and sulfur is critical for maximizing yield potential in durum wheat, as it significantly outperforms the independent effects of either nutrient alone. Therefore, integrating nitrogen and sulfur into fertilization strategies is essential to optimizing durum wheat productivity and minimizing potential nitrogen-related negative impacts.

The relationship between nitrogen application and durum wheat productivity is nonlinear, with nitrogen saturation representing a critical threshold. Beyond this point, additional nitrogen fails to enhance, and may even reduce, grain yield. This threshold is particularly important when considering different sowing times, such as spring versus winter sowing. In the present study, spring-sown varieties showed significant yield improvements when nitrogen rates were doubled, indicating their higher capacity to utilize additional nitrogen. This is likely due to their accelerated growth patterns and enhanced nitrogen uptake during shorter growing seasons. In contrast, winter-sown varieties exhibited a decline in grain yield as nitrogen application reached 100 kg ha^{-1}. Varieties such as GK Julidur and GK Bétadur experienced yield reductions of 12.27% and 18.18%, respectively. These results highlight the importance of variety-specific nitrogen management, with some varieties, such as GK Bétadur, showing greater sensitivity to excessive nitrogen. This suggests that different varieties have distinct nitrogen saturation thresholds, emphasizing the need for adjusted nitrogen strategies to optimize yield.

The pronounced genotype-by-nitrogen (G × N) interaction in durum wheat reinforces the critical role of genetic variability in determining responses to nitrogen fertilization. A variety that excels under high nitrogen conditions may not perform as well under low nitrogen levels, as indicated by the varying genetic value correlations across nitrogen environments. MV Pelsodur exemplifies this with its stable yield performance in both low (7501 kg ha^{-1}) and high nitrogen environments (7439 kg ha^{-1}), demonstrating its exceptional nitrogen use efficiency (NUE). The consistency of this variety, irrespective of nitrogen availability, makes it particularly valuable for regions where nitrogen is limited or where sustainability efforts aim to reduce nitrogen inputs. Varieties like MV Pelsodur, which maintain stable yields under varying nitrogen levels, are crucial for promoting resource-efficient wheat production, especially in areas facing nitrogen constraints or implementing sustainability measures.

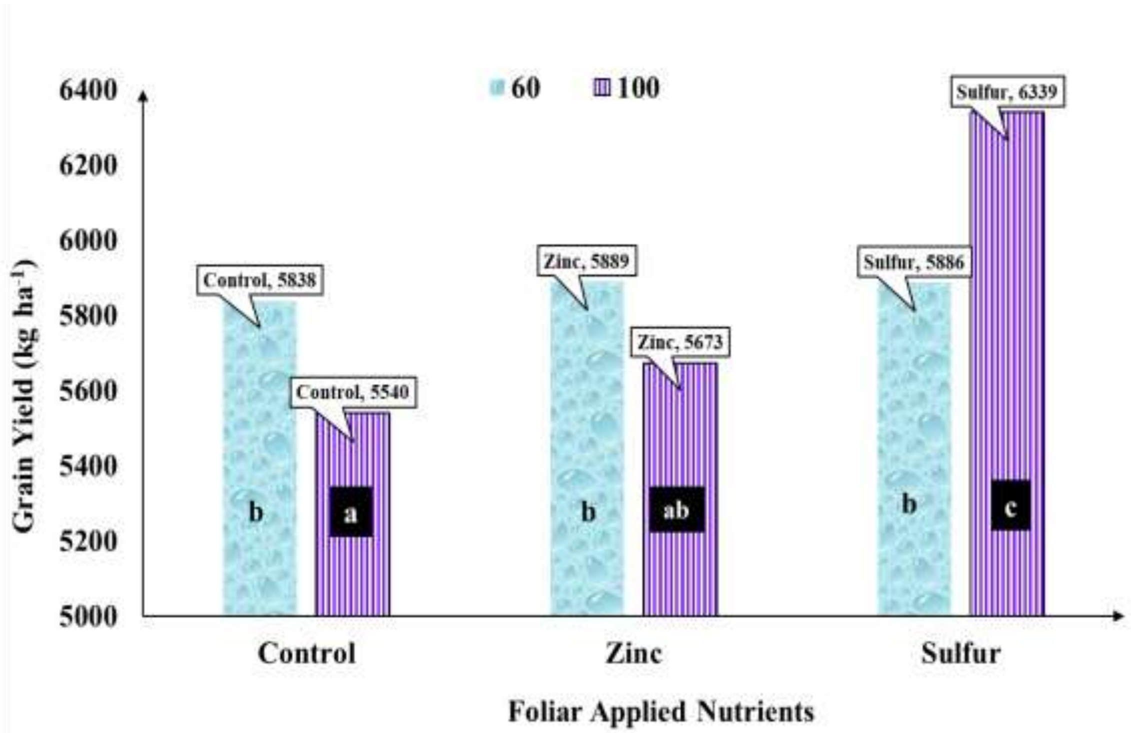


Figure 4. Interactive effects of nitrogen rates and zinc and sulphur additions on grain yield. Treatments sharing the same letter are not significantly different ($p < 0.01$), while different letters indicate significant differences (2022–2023 cropping season).

On the other hand, the contrasting performance of MV Pelsodur and Tamadur under different nitrogen levels highlights the importance of flexible, variety-specific nitrogen management strategies. For varieties like Tamadur, where higher nitrogen inputs significantly boost yield, nitrogen applications should be tailored to maximize productivity without exceeding environmental thresholds. In contrast, varieties like MV Pelsodur, which sustain stable yields under low nitrogen, could benefit from strategies that reduce nitrogen inputs, making them ideal for regions with limited nitrogen availability or those prioritizing sustainability. This study reinforces the agronomic principle that optimizing nitrogen management requires an integrated approach, considering both genetic and environmental factors. Therefore, breeding programs and agronomic practices should focus on developing wheat varieties with improved NUE and nitrogen strategies that maximize yield while minimizing environmental impact. Excessive nitrogen fertilization can often lead to yield plateaus or even declines due to nutrient imbalances, antagonism, or stress on the plant's metabolic systems.

3.3. Varietal and Nutrient Interactions in Durum Wheat Under Drought

The results clearly demonstrate that combining nitrogen with sulfur and zinc (Zn) significantly mitigates the negative effects of excessive nitrogen and enhances grain yield. The observed 14.42% increase in yield with sulfur at high nitrogen levels is consistent with previous studies highlighting sulfur's role in improving NUE. This sulfur-nitrogen synergy not only boosts grain yield but also improves grain quality by optimizing nitrogen metabolism. Sulfur plays a critical role, particularly at higher nitrogen rates, by addressing nutrient imbalances and enhancing NUE, thereby maximizing the benefits of nitrogen fertilization.

The 10% yield increase observed when nitrogen is combined with zinc application was significant. This highlights zinc's ability to mitigate the negative effects of nitrogen saturation, thereby improving the plant's overall nutrient balance and yield potential. This implies the importance of balanced nutrient management, particularly in environments where nitrogen is applied at high levels. The synergistic interaction between nitrogen, sulfur, and zinc in enhancing grain yield in durum wheat indicates the importance of integrated nutrient management approach. The 8.24% to 9.48% yield improvement observed in this study when nitrogen and sulfur were applied together highlights the intricate relationships between these nutrients in promoting optimal plant growth. This synergy, where the combined effects of nutrient co-application exceed the impact of individual nutrient treatments, reinforces the idea that nutrient availability in plants is interdependent. The relatively small yield response to nitrogen or sulfur when applied independently, with only a 1.13% variation between the two treatments, further implies the value of co-fertilization.

In 2021 cropping season, characterized as a dry season, the exogenous application of sulphur fertilizers significantly ($p < 0.05$) enhanced grain yield, particularly the spring-sown varieties (Figure 5). However, the regulatory effect of sulphur on grain yield varied based on the durum wheat varieties response to drought-induced stress. It had been observed that sulphur-containing fertilizer significantly improved grain yield in the variety Tamadur by approximately 12.23%, increasing yield from 4.8 to 5.4 t ha^{-1} compared to the control group (Figure 5). This substantial yield improvement highlights the critical role of sulphur in supporting grain yield under drought conditions.

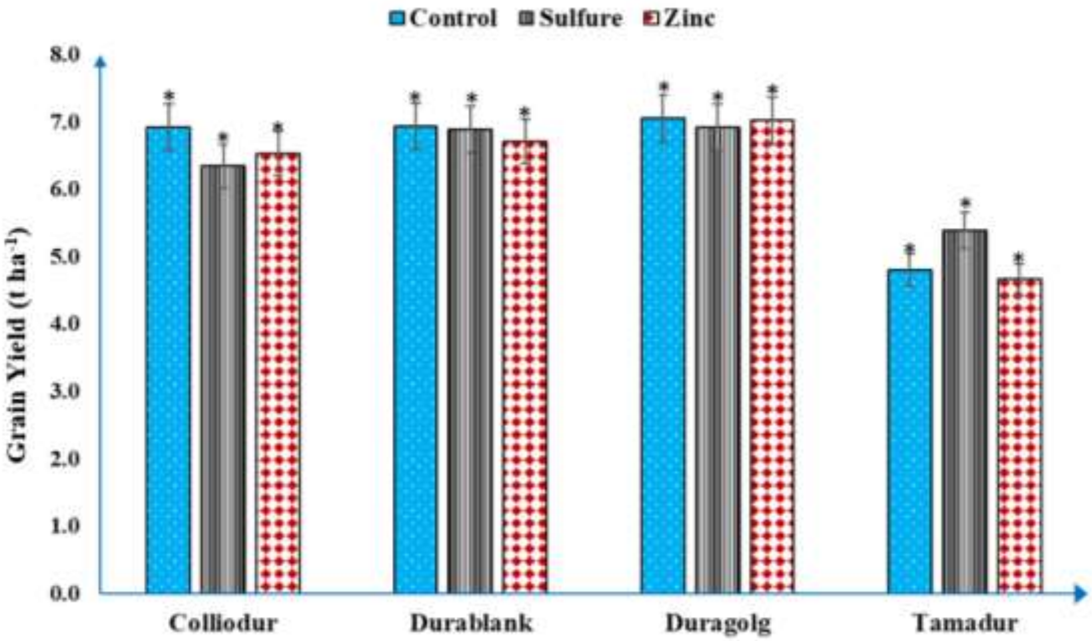


Figure 5. Effects of foliar based zinc and sulphur fertilization on grain yield of different durum wheat varieties under drought condition. Bars indicated with single asterisks are statistically significant at 0.05% (2021 copping season).

3.4. Nitrogen Saturation and its Implications on Crop LAI, SPAD, and NDVI

The interaction between nitrogen rate and durum wheat varieties significantly ($p < 0.05$) influenced LAI, NDVI, and SPAD values, with spring-sown varieties showing a more pronounced positive response to higher nitrogen levels compared to winter-sown varieties. Some winter-sown varieties exhibited minimum values at the higher nitrogen rate (100 kg ha^{-1}), indicating a complex interaction between nitrogen application and winter planting conditions. This suggests that certain winter-sown varieties are less responsive or even negatively affected by higher nitrogen levels due to factors such as varietal characteristics, environmental conditions, and agronomic practices. While nitrogen application improved these traits, increasing rates beyond 100 kg ha^{-1} did not yield further benefits and instead led to declines in LAI, SPAD, and NDVI. In wet conditions, high nitrogen levels appeared to induce physiological stress, as evidenced by reduced chlorophyll content (lower SPAD readings) and diminished canopy growth (lower LAI and NDVI values). This phenomenon, known as nitrogen saturation, highlights the diminishing returns of excessive nitrogen, particularly in moisture-rich environments.

Table 3. The interaction effect analysis between cropping years and nitrogen levels, concerning leaf reflectance traits measured at the various stage, and yield (2021 cropping season).

N Rate (kg ha^{-1})	**Years**	**Tillering**			**Booting**			**Flowering**			**GY (kg ha^{-1})**
		LAI	**NDVI**	**SPAD**	**LAI**	**NDVI**	**SPAD**	**LAI**	**NDVI**	**SPAD**	
60	2022	5.17	0.80	56.08	6.16	0.70	59.19	3.94	0.79	55.40	5543.63
	2023	2.57	0.60	51.21	3.29	0.60	49.10	3.70	0.77	54.12	6198.11
100	2022	6.40	0.81	55.79	7.13	0.71	58.98	4.82	0.84	56.50	5671.47
	2023	2.60	0.57	53.24	3.74	0.57	49.40	3.62	0.78	53.68	6041.68
LSD$_{0.05}$		1.21	0.08	0.94	0.65	0.03	2.49	0.94	0.03	1.14	157.98
CV (%)		23.10	9.20	7.70	24.00	8.30	5.20	20.00	3.80	6.60	7.50

Key to abbreviations: NDVI; Normalized difference vegetative index, LAI; Leaf are index, SPAD; Soil plant development analysis, GPC; Grain protein content; GY; Grain yield (kg ha^{-1}).

The influence of nitrogen rate varied across seasons. During the drought-affected 2022 cropping season, significant improvements ($p < 0.05$) in LAI, NDVI, and SPAD values were observed at both nitrogen rates, with even 60 kg ha^{-1} being sufficient to meet crop nitrogen demands under water-limited conditions (Table 3). Conversely, in the excessively wet 2023 season, both nitrogen rates resulted in minimal values for these traits, suggesting that excessive soil moisture hindered crop growth, regardless of nitrogen application. The contrasting responses between the two seasons indicates the dominant role of climatic conditions in shaping vegetation growth and nitrogen utilization. While nitrogen had a marked effect during drought, the excessive moisture in 2023 overrode its influence, emphasizing the need for adaptive nitrogen management tailored to seasonal variability.

Across both cropping seasons, the maximum values for LAI, NDVI, and SPAD were recorded during the booting and tillering stages, with a decline in these traits as the crop progressed to the flowering stage. Although both seasons exhibited a similar trend of fluctuating trait values under varying nitrogen rates, the 2022 season, characterized by drought, showed higher LAI, SPAD, and NDVI values at the lowest nitrogen rate compared to the wetter 2023 season (Table 3). A significant interaction effect was observed among durum wheat varieties, nitrogen rates, and developmental stages for these traits. However, the genetic response of the tested varieties was inconsistent; some varieties exhibited high LAI and SPAD values but lower NDVI values across developmental stages. For example, MV Pennedur demonstrated higher LAI and NDVI under high nitrogen rates during the booting stage, but at the tillering stage, it showed low values under lower nitrogen rates, responding positively to higher nitrogen rates.

The contrasting responses between the wet 2023 and dry 2022 seasons highlight the complexity of nitrogen-crop interactions. During the dry 2022 season, lower nitrogen rates (60 kg ha^{-1}) proved more beneficial, resulting in higher LAI, SPAD, and NDVI values compared to the wetter 2023 season. This suggests that in dry conditions, lower nitrogen rates can reduce nitrogen leaching and better synchronize nitrogen availability with crop demand. On the other hand, excessive soil moisture in 2023 likely limited nitrogen efficiency, reducing its impact on crop growth. Additionally, the study reinforces the limitations of NDVI as a growth indicator in dense wheat canopies under high nitrogen and wet conditions. This limitation diminishes NDVI's utility for real-time nitrogen management in high-biomass crops, particularly during later growth stages.

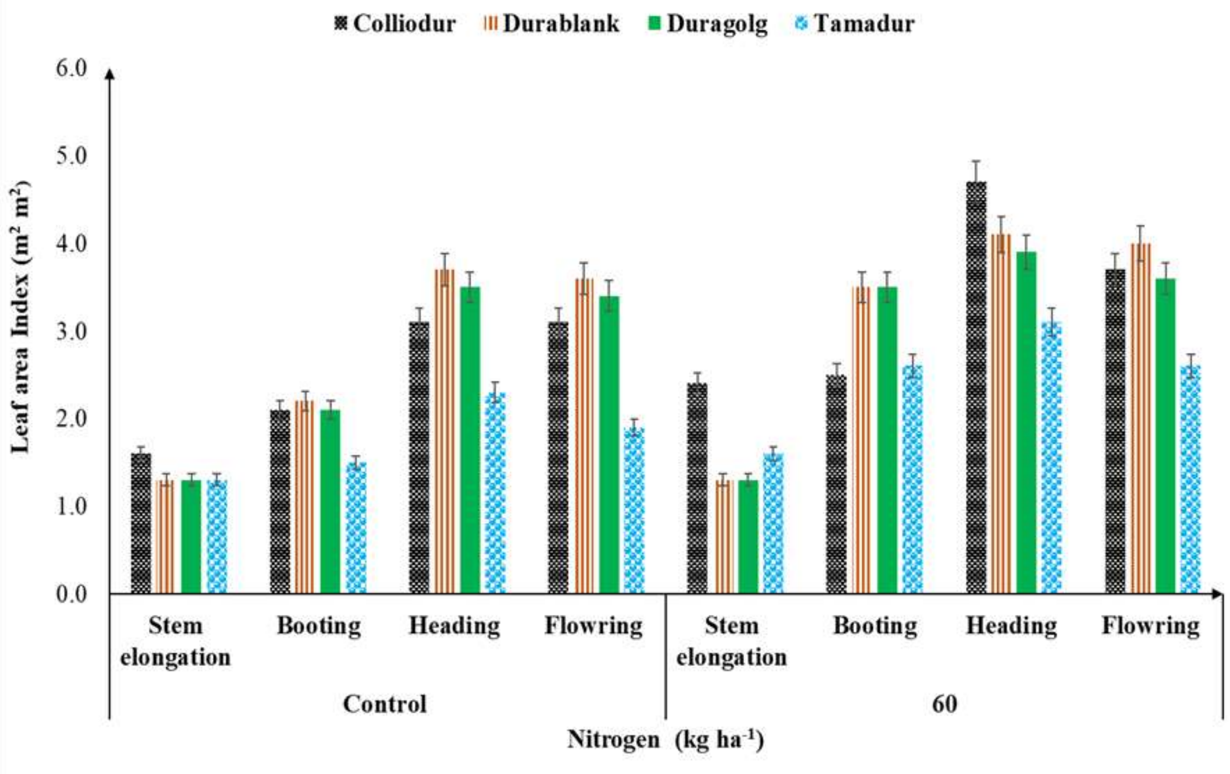


Figure 6. Interaction effects of nitrogen application and varietal differences on LAI across developmental stages (statistical significance at the 0.05 % level of probability, 2021 cropping season).

The analysis of variance revealed a significant interaction effect between nitrogen application and durum wheat varieties, particularly for spring-sown varieties (Figure 6). Nitrogen application at 60 kg ha^{-1} did not significantly affect LAI during stem elongation and flowering, likely due to sufficient early-season nitrogen, reduced uptake efficiency, or a physiological shift toward reproductive growth. This pattern reflects the natural variation in LAI between leaf production and senescence phases, with the decline likely resulting from the transition from fully green leaves to a mix of green, yellow, and senescent leaves. These findings suggest that nitrogen management strategies should prioritize earlier growth stages, particularly tillering and booting, to maximize its impact on leaf development and overall productivity. The stage-specific responses of durum wheat to nitrogen fertilization highlight the importance of precise nutrient timing. For example, MV Pennedur exhibited a marked improvement in LAI and NDVI at higher nitrogen rates during the tillering stage, highlighting nitrogen's role in early canopy development, which is critical for yield potential. At the booting stage, nitrogen’s influence shifted toward enhancing SPAD values, reflecting improved chlorophyll synthesis and photosynthetic capacity—essential for grain filling and reproductive success.

The genetic variability in nutrient uptake and growth dynamics, as demonstrated by MV Pennedur, emphasizes the need for variety-specific nitrogen management strategies. This variety responded better to higher nitrogen levels during early stages, suggesting its higher nitrogen demand during these critical periods. In contrast, other varieties may reach optimal growth with lower nitrogen inputs, depending on genetic traits and environmental conditions. These results emphasize the importance of adjusting nitrogen management practices based on both environmental factors (i.e., drought vs. wet seasons) and the specific growth stages of durum wheat varieties. For nitrogen-sensitive varieties like MV Pennedur, optimizing nitrogen application at key stages such as tillering and booting can enhance canopy development and overall yield potential.

In water-limited environments, nitrogen management must incorporate water-use efficiency strategies, as moisture availability becomes a dominant factor in nutrient uptake and plant growth. Therefore, integrating nitrogen application with crop developmental needs and environmental conditions is essential for maximizing durum wheat productivity while addressing challenges such as climate variability and resource constraints. This comprehensive, synchronized approach can help ensure that durum wheat farming remains productive and sustainable, even in the face of changing environmental conditions.

3.5. The effect of nutrient management on yield associated metrics

The analysis of variance revealed that the interaction effects among nitrogen application rate, varietal differences, and foliar nutrient applications were significant ($p < 0.001$) for the number of spikes produced per square meter (Table 1; Table 4). However, the main effect of nitrogen application rate alone did not show a statistically significant ($p < 0.05$) impact on spike density (SPD) (Table 4). The significant interactions between the imposed factors imply that the response of durum wheat spike production to nitrogen application varies depending on the variety and the additional nutrients applied. This means that certain varieties may respond better to nitrogen fertilization when combined with foliar applications of nutrients such as sulphur or zinc. The absence of a statistically significant main effect for nitrogen application rate suggests that simply increasing nitrogen levels does not uniformly enhance spike production across all conditions. The evaluation of nitrogen application rates revealed significant variability in spike production among durum wheat varieties, indicating the crucial role of nitrogen in optimizing this crucial yield metrics. The highest spike production was observed in the varieties MV Vékadur (550.9 spikes/m²), GK Julidur (526.9 spikes/m²), and MV Pennedur (518.7 spikes/m²) when treated with a high nitrogen rate of 100 kg ha^{-1} (Table 1). This indicates that these varieties respond positively to increased nitrogen levels, likely due to their enhanced ability to utilize nitrogen for spike development and growth.

Table 4. The main effect of nitrogen, foliar application of zinc and sulphur, as well as varietal difference on yield and yield attributed traits.

Treatments			**SPD (m^2)**	**SPL (cm)**	**AWL (cm)**	**PH (cm)**	**GPC (%)**	**GY (kg ha^{-1})**
Nitrogen (kg ha^{-1})		60	452.3	5.95	9.24	77.67	14.98	5870.87
		100	467.3	6.59	8.59	79.30	15.46	5856.58
		LSD$_{0.05}$	25.85	0.27	0.81	3.31	1.11	143.58
		CV (%)	1.6	1.20	2.69	1.20	2.10	0.70
Nutrients		Control	458.7	6.18	8.86	77.73	15.15	5688.68
		Zinc	456.9	6.29	8.93	79.12	15.28	6112.30
		Sulphur	463.9	6.34	8.93	78.61	15.23	5790.19
		LSD$_{0.05}$	4.67	0.16	0.18	0.836	0.15	226.049
		CV (%)	2.6	4.8	5.1	2.8	3.50	2.9
Varieties	**Winter**	GK Bétadur	505.10	6.59	9.24	77.27	15.58	5185.63
		GK Julidur	516.70	5.81	9.92	74.07	15.83	5960.28
		MV Hundur	500.40	7.09	7.81	87.43	15.36	6304.32
		MV Pennedur	469.80	6.77	9.47	84.99	15.07	6416.66
		MV Vékadur	513.00	6.11	8.37	85.70	15.07	6429.77
		MV Pelsodur	531.20	7.59	10.3	86.81	14.32	7469.85
	Spring	Durablank	355.70	5.46	8.40	69.88	15.58	4801.90
		Duragold	365.20	5.46	8.35	70.33	15.38	5309.70
		Tamadur	381.30	5.55	8.37	69.90	14.80	4895.40
		LSD$_{0.05}$	12.29	0.44	0.47	3.770	0.63	292.710
		CV (%)	2.3	6.0	4.5	4.1	2.6	7.5

The analysis of spike density (spikes/m²) in relation to grain yield revealed a surprising pattern. Varieties with the highest spike densities did not always achieve the highest grain yields (Table 1 and 4). For instance, MV Pelsodur, with the lowest spike density (479.60 spikes/m²), produced the highest yield (7438.99 kg ha^{-1}). In contrast, varieties such as MV Vékadur, GK Julidur, and MV Hundur, which had higher spike densities (550.90, 526.90, and 501.60 spikes/m², respectively), yielded less (6402.80, 5570.78, and 6098.42 kg ha^{-1}) under high nitrogen conditions. Interestingly, GK Bétadur, the lowest yielding winter-sown variety, outperformed in low nitrogen conditions compared to high nitrogen environments (Table 4). A similar trend was observed in spring-sown varieties. Despite Tamadur having the highest spike density (381.30 spikes/m²), Duragold (365.20 spikes/m²) showed greater yield potential, while Durablank had the lowest spike density (355.70 spikes/m²) (Table 4).

The inverse relationship between spike density and grain yield in certain varieties challenges the assumption that higher spike density directly correlates with increased yield. Despite its lower spike density, MV Pelsodur achieved superior yields (7438.99 kg ha$^{-1)}$. High spike density increases the number of potential grain sites but intensifies competition for nutrients, limiting resources for grain filling and reducing yield potential. Varieties like MV Pelsodur, with lower spike density, may allocate resources more efficiently toward grain filling, reducing competition and increasing grain size and weight. The variability in spike production based on nitrogen application highlights the need for adjusted nutrient management strategies. Varieties like MV Vékadur, GK Julidur, and MV Pennedur showed higher spike densities under high nitrogen (100 kg ha$^{-1)}$, suggesting effective nitrogen allocation toward spike development. However, the lack of a significant nitrogen effect on spike density across varieties points to nitrogen saturation, where further increases in nitrogen input do not yield higher spike density or grain yield.

Spike length, an important determinant of grain number and yield, was influenced by both genetic and environmental factors, including nutrient availability. In this study, spike length was significantly ($p < 0.05$) affected by the interaction between nitrogen application rate and variety. Winter-sown varieties, such as MV Pelsodur, showed the longest spike length (7.72 cm at high N; 7.14 cm at low N), followed by MV Vékadur (7.12 cm at high N; 7.07 cm at low N). In contrast, spring-sown varieties like Tamadur (6.57 cm) and Durablank (6.47 cm) had the longest spikes under high nitrogen conditions. These results suggest that winter-sown varieties may have more stable spike lengths due to their longer growth period, which allows for more consistent nutrient absorption. The interaction between nitrogen rates and varietal differences in spike length highlights the complex genetic and environmental factors affecting durum wheat growth. Winter-sown varieties like MV Pelsodur and MV Vékadur demonstrated longer spikes under high nitrogen conditions, indicating their ability to utilize increased nitrogen for enhanced spike elongation. The ability to elongate spikes is often linked to higher yield potential, as longer spikes typically support more grain.

The spring-sown varieties, such as Tamadur, also responded positively to high nitrogen, suggesting nitrogen's key role in enhancing spike length across different genotypes. However, the differing responses between spring- and winter-sown varieties may reflect distinct growth patterns influenced by sowing time, temperature, photoperiod, and soil moisture availability, which affect nitrogen uptake and spike elongation dynamics. The differential response to foliar nutrient applications, particularly zinc and sulfur, highlights the need to integrate genetic variability into nutrient management strategies. Zinc application improved spike length in winter varieties like MV Pelsodur and MV Vékadur, supporting the role of zinc in promoting cellular metabolism, hormone balance, and nutrient uptake. Sulfur application also benefited spike elongation, likely by enhancing protein synthesis and enzyme activity. However, the varied response of MV Hundur to zinc and sulfur applications indicates that the effectiveness of foliar nutrients depends on the variety, emphasizing the need for variety-specific nutrient management strategies.

The study revealed significant variation in plant height, with winter-sown varieties like MV Hundur and MV Pelsodur being notably taller. This suggests that genetic factors play a key role in determining plant height, as nitrogen application did not significantly impact this trait. The variation in height could stem from inherent genetic differences in the varieties, indicating that both genetics and foliar nutrient applications are crucial in shaping this characteristic. The lack of a significant nitrogen effect on plant height in spring-planted varieties may be due to environmental factors, such as fluctuations in photoperiod and temperature, which can override genetic potential and alter physiological responses. These conditions, common in spring-sown varieties, can limit growth even with higher nitrogen availability or foliar nutrient applications. Overall, the interaction between nitrogen rates, foliar nutrients, and varietal genetics highlighting the complex relationship between genetic traits and nutrient management in durum wheat.

The analysis of variance further showed that the influence of foliar nutrient application and genetic differences was significantly impacted plant height, whereas the main effect of nitrogen application rate did not show a significant influence (Table 4). The lack of significant impact from nitrogen application might be attributed to sufficient baseline nitrogen levels in the soil or the potential for other nutrients to be limiting factors in height growth. A significant variation in plant height was observed among winter-sown durum wheat cultivars, with MV Hundur (87.43 cm), MV Pelsodur (86.81 cm), and MV Vékadur (85.70 cm) exhibiting notably taller plants compared to GK Julidur (74.04 cm) and GK Bétadur (77.27 cm). In contrast, for spring-planted varieties, such as Durablank (69.88 cm), Duragold (70.33 cm), and Tamadur (69.90 cm), no statistically significant effect on plant height was observed (Table 4). This could be attributed to the different environmental conditions encountered during the spring growing season or inherent genetic characteristics that may limit height regardless of nutrient application.

3.6. Impact of Nutrient Supply, Varieties, and Seasons on Protein and Zinc Content

Analysis of variance revealed that interaction effects such as nitrogen application combined with varietal differences, and foliar zinc and sulphur applications were statistically significant ($p < 0.05$) in influencing grain protein levels (Figure 5). However, the main effects of zinc, sulphur, 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 (Table 5). The significant interaction between nitrogen application and varietal differences indicates the importance of adjusting nitrogen rates to specific durum wheat varieties to optimize protein content. Additionally, the interaction of foliar zinc and sulphur applications with varietal differences indicates that specific nutrient management strategies are necessary to enhance grain protein content.

When assessing the allometric relationships of grain quality traits relative to biological potential, it was observed that varieties with higher protein content typically had lower yield potential, while high-yielding varieties accumulated lower grain protein content, likely due to the dilution effect. The highest grain protein content was found in GK Julidur, reaching 16.55% when sulphur was combined with a high nitrogen rate, and 16.36% when zinc was combined with a high nitrogen rate (Figure 7; Table 5). MV Vékadur followed with 16.20% protein content under similar conditions. In contrast, MV Pelsodur consistently had the lowest grain protein content across all nutrient treatments—14.20% with sulphur and 13.97% with zinc combined with a high nitrogen rate—despite its high-yielding potential (Table 5). This pattern highlights the trade-off between grain yield and protein content, as high-yielding varieties often have lower protein content, while varieties with higher protein content are generally lower-yielding.

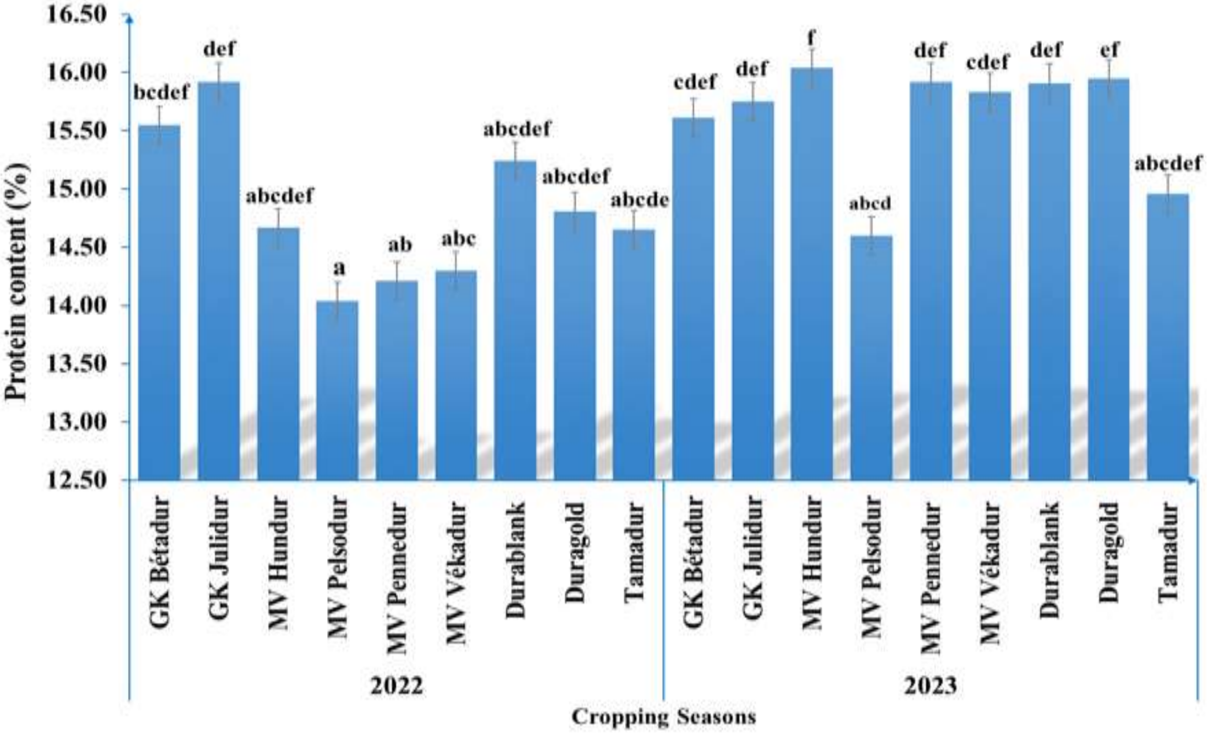


Figure 7. The interactive effect of crop genetic variation and differences in cropping season on grain protein content. Bars with different letters show significance at the 0.05 level, while those with the same letters indicate no significant effect on grain protein content

The comparative analysis of grain protein content clearly shows that both genetic factors and growing seasons significantly influence protein levels in durum wheat (Figure 6). The larger variation in protein content across varieties (10.54%) compared to between growing seasons (5.40%) highlights the dominance of genetic variability in determining protein content, despite environmental influences (Table 5). The significant genotype-environment interactions observed suggest that while genetic factors are key drivers, environmental factors can amplify or constrain genetic potential, especially in suboptimal conditions. In the 2023 cropping season, with higher rainfall and more favorable conditions, the maximum grain protein content reached 15.62%, significantly higher than the 14.82% observed during the drier 2022 season. This difference suggests that wetter conditions in 2023 were more conducive to protein development in durum wheat. The increase in grain protein content during the wetter 2023 season compared to the drier 2022 season emphasizes the strong relationship between water availability and protein synthesis in durum wheat.

Table 5. The interaction effect of nitrogen application rate, nutrient application and variation in genetic difference among durum wheat varieties on grain protein content.

Varieties	**60 (kg ha^{-1})**			**100 (kg ha^{-1})**		
	Control	**Sulphur**	**Zinc**	**Control**	**Sulphur**	**Zinc**
GK Bétadur	15.18	15.44	15.36	15.94	16.00	15.57
GK Julidur	14.89	14.97	15.51	16.71	16.36	16.55
MV Hundur	15.05	14.57	15.07	15.87	15.70	15.88
MV Pelsodur	13.98	15.00	14.41	14.36	14.20	13.97
MV Pennedur	14.75	15.43	15.16	14.56	15.50	15.02
MV Vékadur	14.90	14.23	14.15	15.48	15.44	16.20
Durablank	15.66	15.92	15.81	15.38	15.57	15.11
Duragold	15.50	14.91	14.87	15.76	15.37	15.88
Tamadur	13.96	14.92	14.84	14.73	15.51	14.85
LSD$_{0.05}$	1.13	1.13	1.13	1.13	1.13	1.13
CV (%)	3.5	3.5	3.5	3.5	3.5	3.5

The results indicated that grain zinc concentration was significantly influenced by both varietal differences and the growing environment. When analyzing the main effect of genetic influence among the tested durum wheat varieties, Durablank exhibited the highest grain zinc concentration at 34.70 mg kg$^{-1.}$ In contrast, the lowest zinc concentrations were observed in MV Pelsodur (23.0 mg kg$^{-1)}$ and GK Julidur (23.8 mg kg$^{-1)}$. The variability in grain zinc concentration between the tested varieties was 50.87%, indicating the strong genetic component in zinc accumulation in durum wheat. The significant variability in grain zinc content among the tested varieties highlights the influence of genetic selection on micronutrient accumulation, with variety Durablank consistently exhibiting the highest zinc levels. The 50.87% genetic variation in zinc concentration among the tested varieties emphasizes the importance of utilizing genetic diversity to improve the nutritional profile of durum wheat. Durablank's superior performance, compared to high-yielding varieties like MV Pelsodur and GK Julidur, highlights the potential of genetic selection to enhance grain zinc concentration without compromising yield.

The environmental component, particularly the influence of growing conditions such as water availability, further complicates zinc biofortification efforts. The results show that zinc accumulation was higher during the drought year of 2022 than in the wet year of 2023 across all varieties. Durablank, for instance, exhibited its highest zinc content during the dry season, recording 35.79 mg kg$^{-1,}$ compared to 33.61 mg kg^{-1} in the wet season. The increase in zinc concentration during drier conditions suggests that limited water availability may boost nutrient concentration in the grain, possibly due to reduced biomass or stress-induced mechanisms that enhance nutrient uptake efficiency. These varieties could be better adapted to drought-prone regions where water availability is limited. In contrast, high-yielding winter-sown varieties (MV Pelsodur) showed lower zinc concentrations, reflecting a possible trade-off between yield potential and nutrient density.

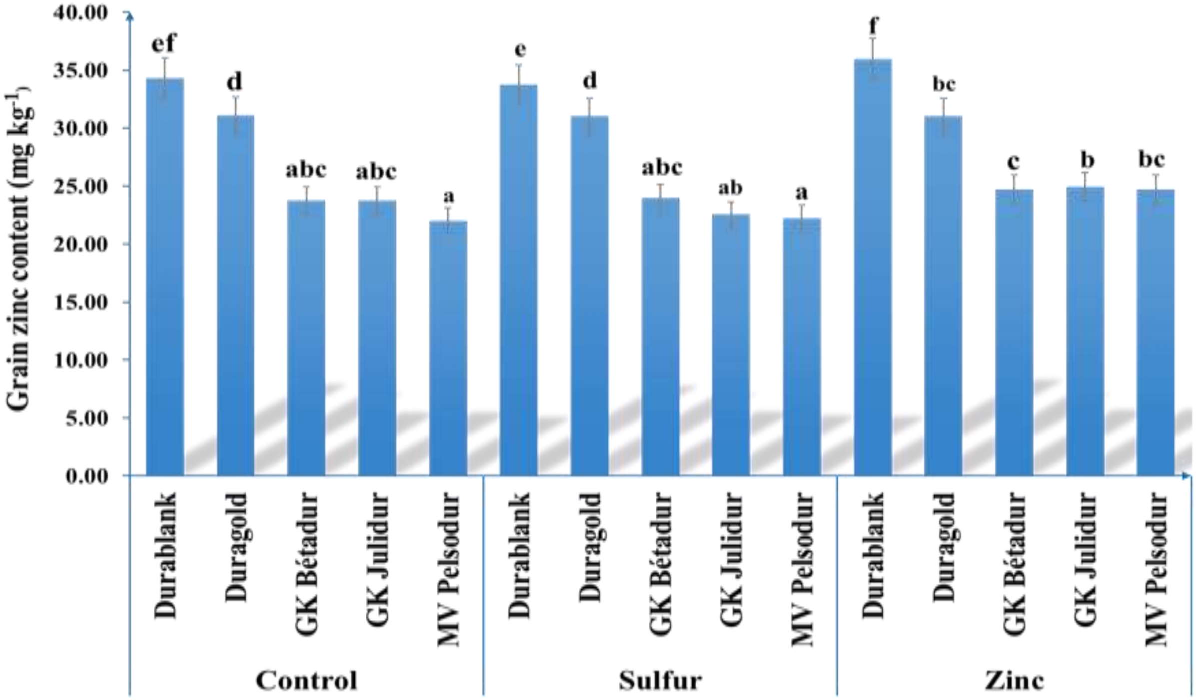


Figure 8. Illustrates the impact of genetic diversity within durum wheat varieties on agronomic biofortification (2022-2023 cropping season)

The interaction between foliar zinc and sulfur application and the genetic makeup of durum wheat varieties highlights the potential of integrating genetic selection with targeted agronomic interventions. The significantly higher grain zinc concentration in Durablank after foliar zinc application suggests a strong varietal ability to uptake and translocate zinc into the grain, even under varying environmental conditions. In contrast, high-yielding varieties like MV Pelsodur exhibited a lower capacity for zinc accumulation, even when treated with zinc and sulfur. The strong genetic influence on zinc accumulation suggests that breeding programs should prioritize zinc-efficient varieties including Durablank, particularly in water-stressed environments. However, the lower zinc levels in high-yielding varieties (MV Pelsodur), even with zinc and sulfur applications, reveal an ongoing challenge in balancing yield with nutrient density. The positive impact of foliar zinc and sulfur applications across all varieties shows that targeted nutrient management can enhance grain zinc levels and complement genetic approaches. This strategy can be particularly valuable for varieties that are less efficient at naturally accumulating zinc, providing a means to improve nutritional content without sacrificing yield. The superior performance of Durablank, particularly under drought conditions, suggests that spring-sown varieties may hold significant potential for zinc biofortification in regions facing water scarcity. At the same time, the lower zinc accumulation in MV Pelsodur highlights the ongoing challenge of balancing yield and nutritional quality.

The interaction between cropping years and durum wheat varieties was also found to significantly affect grain zinc concentration (Figure 8). The highest zinc concentration was observed in the variety Durablank, which recorded 35.79 mg kg^{-1} during the drought year of 2022. In contrast, the lowest grain zinc concentrations were observed in the varieties MV Pelsodur (24.84 mg kg$^{-1)}$ and GK Julidur (24.63 mg kg$^{-1)}$ under the same drought conditions. During the wet cropping season of 2023, Durablank outperformed other varieties in grain zinc accumulation, reaching a maximum concentration of 33.61 mg kg^{-1} (Figure 8). This suggests that spring-sown durum wheat varieties, such as Durablank, are more efficient at accumulating grain zinc than high-yielding winter-sown varieties like MV Pelsodur and GK Julidur. The varieties accumulated more zinc in the grain during the dry season compared to the wet season. Grain zinc concentration varied by 45.31% between varieties in the dry season, increasing to 58.99% in the wet season, highlighting a greater disparity in zinc accumulation under differing environmental conditions. These results indicate that environmental factors, especially water availability, play a crucial role in determining the ability of durum wheat varieties to accumulate zinc in the grain. Spring-sown varieties, especially under drought conditions, appear to be better suited for zinc biofortification efforts compared to high-yielding winter-sown varieties.

A significant interaction effect was observed between foliar application of zinc, sulfur, and the tested durum wheat varieties (Figure 9). Zinc application positively influenced grain zinc concentration across all treatments, but varietal responses varied substantially. The maximum grain zinc concentration was recorded in the variety Durablank, which exhibited a significantly higher zinc content when treated with zinc-containing fertilizers (Figure 8). This suggests a strong varietal ability to uptake and translocate zinc into the grain under foliar zinc application. In contrast, the high-yielding variety MV Pelsodur demonstrated the lowest grain zinc concentration, even when subjected to the same zinc and sulfur fertilization regime. These findings show that while MV Pelsodur achieves higher grain yields, it is less efficient at accumulating zinc in the grain compared to Durablank under similar agronomic conditions.

3.7. Principal Component Analysis (PCA)

Principal component analysis (PCA) identified distinct patterns of trait associations that influenced grain yield (GY) in durum wheat varieties. A strong positive correlation was found between GY and SPAD values at the tillering stage (SPAD_T), particularly in the upper-left quadrant of the biplot (Figure 9). Winter-sown varieties, such as MV Pelsodur, MV Hundur, and MV Vékadur, were clustered near this group, indicating efficient chlorophyll utilization early in growth, which contributed to their high yield potential.

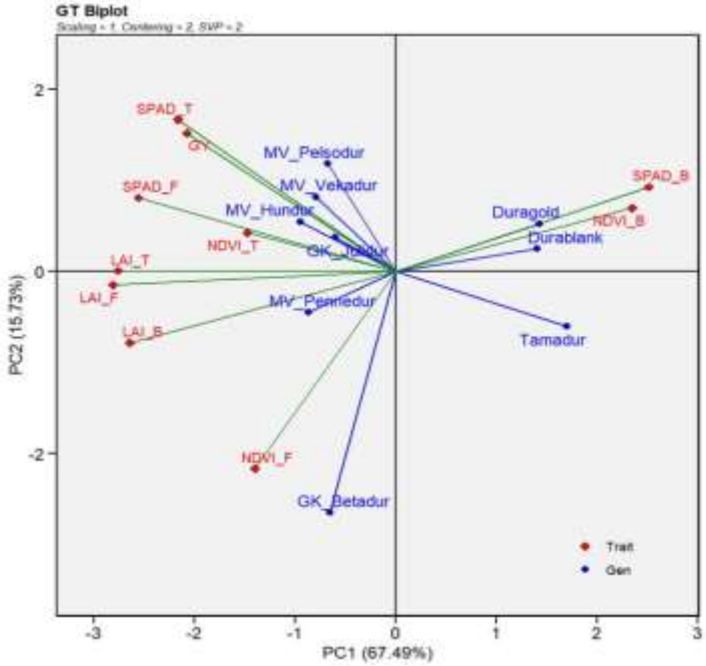


Figure 9. Principal Component Analysis biplot illustrating the relationship between durum wheat genotypes (blue dots) and traits (red diamonds) across different growth stages. The first two principal components (PC1: 67.49% and PC2: 15.73%) together explain 83.22% of the total variability, emphasizing genotype performance and trait associations, particularly for yield (GY), chlorophyll content (SPAD), canopy vigor (NDVI), and leaf area index (LAI).

In contrast, early-stage canopy vigor, as reflected by SPAD and NDVI values at the booting stage (SPAD_B and NDVI_B), was positioned in the upper-right quadrant, where spring-sown varieties like Durablank and Duragold were located. These varieties showed strong early canopy establishment, making them well-suited for environments with rapid early-stage growth demands, although their yield potential appeared lower compared to winter-sown varieties. The analysis also identified Tamadur as drought-sensitive, with a stronger association with SPAD values at booting but weak correlations with NDVI-related traits. LAI measurements at booting, tillering, and flowering were located in the lower-left quadrant, suggesting that a larger leaf area during these stages did not necessarily correlate with increased grain yield or chlorophyll content, indicating that LAI's influence on productivity may be limited, especially under stressful environmental conditions.

4. New Scientific Results

The new scientific results derived from this research represent a substantial contribution to the existing body of knowledge within the field. These results provide a deeper understanding of the critical aspects examined, offering novel perspectives while advancing both theoretical frameworks and practical applications.

1. This study highlights a pioneering concept of nitrogen-insensitive yield stability in durum wheat, with MV Pelsodur demonstrating remarkable NUE. Unlike many varieties that exhibit yield variability with changing nitrogen levels, MV Pelsodur achieved consistently high yields at both low (7501 kg ha^{-1} at 60 kg ha^{-1} N) and high nitrogen rates (7439 kg ha^{-1} at 100 kg ha^{-1} N). This suggests that MV Pelsodur possesses advanced nitrogen uptake and utilization mechanisms, enabling it to maintain productivity regardless of nitrogen input variations. This novel model of nitrogen efficiency not only minimizes dependency on high nitrogen inputs, potentially lowering production costs and environmental impacts but also showcases a pathway for breeding programs aimed at enhancing NUE in durum wheat.

2. In dry seasons, the combination of a high nitrogen rate with sulphur application led to substantial yield increases in varieties MV Vékadur and MV Pennedur, with yield boosts of 22.02% and 27.75%, respectively, compared to the control. This improvement indicates a synergistic effect of nitrogen and sulphur under water-limited conditions, suggesting that sulphur can enhance nitrogen utilization in these conditions.
3. In years with adequate moisture, such as 2023, the higher nitrogen rate resulted in an 11.17% yield increase, demonstrating the variety's capacity to efficiently utilize nitrogen under favorable conditions. In contrast, during dry seasons including 2022, the benefits of this nitrogen application were even more pronounced, leading to yield improvements of up to 21.11%. This indicates that high nitrogen rates can enhance grain yield by approximately 11.17% to 21.11%, depending on the moisture conditions of the cropping season, particularly for spring-sown durum wheat varieties.
4. Analysis of spike production relative to grain yield revealed that varieties with higher spike densities did not always yield more grain. For example, MV Pelsodur, with the lowest spike density (479.60 spikes/m²), achieved the highest yield of 7438.99 kg ha^{-1}, while varieties with higher spike densities, such as MV Vékadur, GK Julidur, and MV Hundur (550.90, 526.90, and 501.60 spikes/m²), yielded less (6402.80, 5570.78, and 6098.42 kg ha^{-1}, respectively)

under high nitrogen conditions. These results suggest that spike density alone is not a reliable predictor of yield, and agronomic strategies should consider additional factors such as nitrogen use efficiency and variety-specific traits to optimize yield.

5. The study establishes a significant correlation between SPAD readings and grain protein content in durum wheat. Maintaining SPAD values between 53.5 to 62.3 during the heading stage has been identified as crucial for achieving the standard whole grain protein content of approximately 12%. This correlation indicates the value of using SPAD readings as a reliable tool for predicting and managing grain protein levels.
6. In wet seasons, the variety MV Pelsodur exhibited remarkable nitrogen-use efficiency, achieving high yields (8,952.81 kg ha^{-1} representing a 6.54% increase) with a reduced nitrogen application rate of 60 kg ha^{-1}, without requiring supplemental zinc or sulphur fertilizers. This suggests that MV Pelsodur possesses genetic traits that enhance nutrient uptake or retention efficiency, enabling resilience to nutrient leaching or dilution effects in high-moisture conditions. Increasing nitrogen rates beyond 60 kg ha^{-1} or supplementing with additional nutrients did not yield further agronomic or economic benefits. These results indicate that optimal nitrogen management alone is sufficient to maximize the yield potential of MV Pelsodur under favourable, moisture-rich conditions, offering a cost-effective and sustainable strategy for durum wheat production in the study area.
7. The results clearly demonstrated that Zn biofortification in durum wheat, achieved through optimal soil nitrogen and foliar zinc management in combination with suitable varieties, can maintain high grain yields with reduced nitrogen input. Simultaneously, this approach enhances the zinc concentration and bioavailability, ultimately improving the health benefits of whole grain.
8. The application of foliar sulphur fertilizers during the flag leaf stage under the potential environment (2023) has a significantly more pronounced positive effect on the grain yield of drought-sensitive durum wheat varieties. The drought-sensitive variety Tamadur showed a remarkable yield improvement of 17.28%, reaching 6224.19 kg ha^{-1} compared to the control. In contrast, the drought-tolerant variety Duragold showed a more modest yield increase of 10.4%, reaching 6319.18 kg ha^{-1}. These findings suggest that sulphur fertilization is particularly effective in improving drought tolerance in sensitive varieties, as the enhancement in yield was more substantial in Tamadur compared to Duragold.

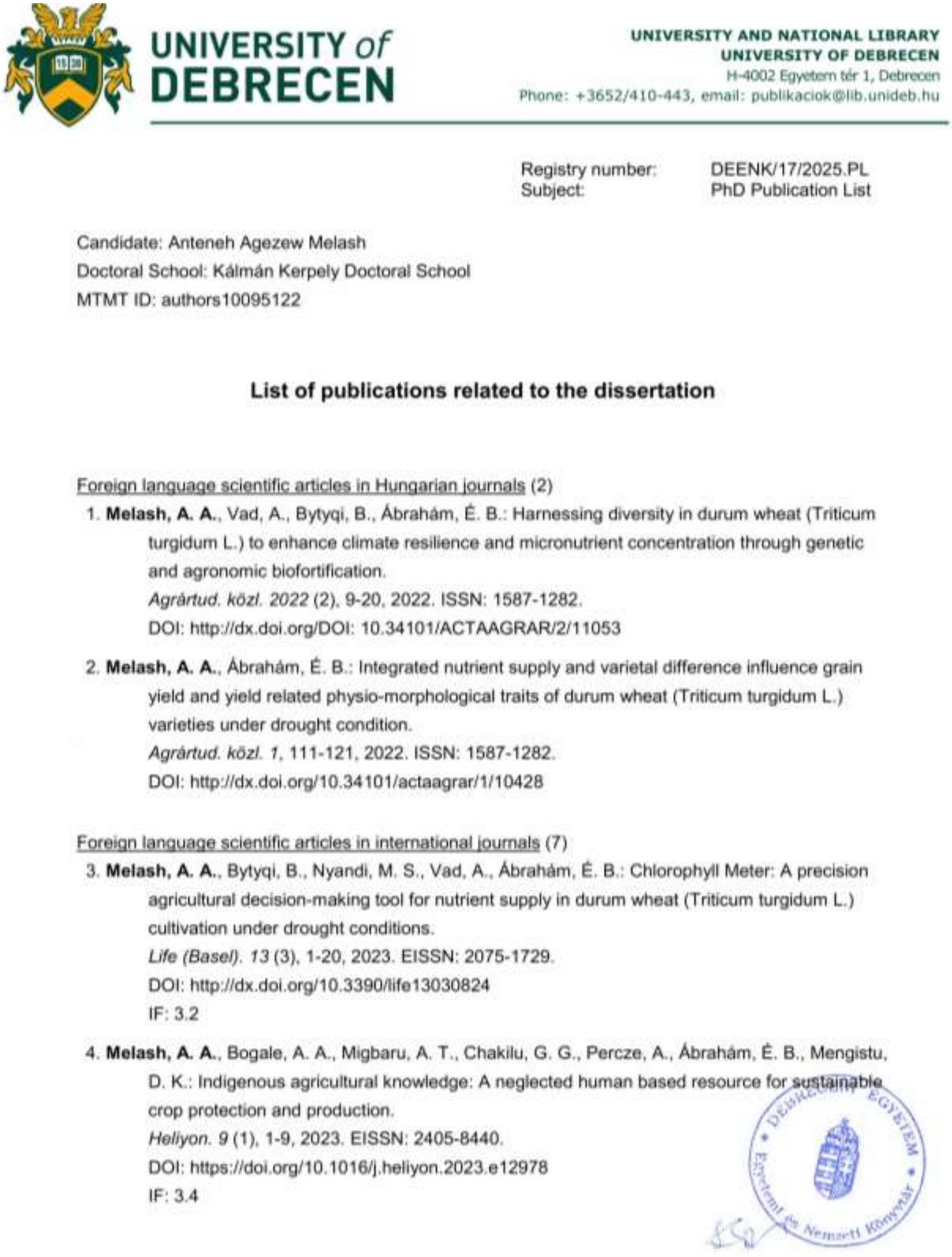
5. PRACTICAL UTILIZATION OF RESULTS

Applying these practical approaches will enable agronomists, and producers to optimize yield and grain quality, promoting more sustainable agricultural practices.

1. The use of remote sensing technologies, such as NDVI profiling, can be valuable for farmers in assessing the health and vigor of durum wheat crops. Hence, regular monitoring of NDVI profiles can provide insights into the crop's condition and help identify stress levels early on, allowing for timely interventions.
2. In regions with limited nitrogen availability, varieties such as MV Pelsodur are recommended due to their efficient nitrogen utilization and consistent high yields. MV Pelsodur demonstrates stable performance across various nitrogen levels, making it an ideal choice for areas with low nitrogen availability or for systems aimed at reducing fertilizer inputs. On the other hand, more responsive varieties, such as Tamadur, may be better suited for regions where higher nitrogen inputs can be sustainably managed. This guidance assists crop breeders, agronomists, and producers in selecting the most suitable varieties for local soil and climatic conditions, ultimately promoting both productivity and sustainability.
3. The spring-sown varieties of durum wheat have shown enhanced responses to higher nitrogen levels, with yield gains of up to 30.48%, due to their efficient nitrogen uptake in cooler conditions. On the other hand, winter-sown varieties showed limited yield increases under high nitrogen, indicating they may have reached a threshold of nitrogen utilization. Hence, farmers can apply these insights by adjusting nitrogen rates according to variety and planting season, ensuring that only the necessary levels are applied to maximize yield without risking nitrogen saturation.
4. In water-limited environments, consider increasing nitrogen application to meet the higher demand, while in wet seasons, careful management is needed to prevent adverse effects like lodging and nutrient leaching.
5. The observation that MV Pelsodur, despite having a lower spike density, produced the highest grain yield emphasizes the importance of selecting wheat varieties based on comprehensive performance indicators, rather than relying solely on spike density. This could help farmers choose varieties with higher overall yield potential and better adaptability to high nitrogen conditions.

6. The results challenge the conventional assumption that higher spike density directly correlates with higher yield. This may lead to a revision of yield prediction models, integrating additional factors such as nitrogen use efficiency, growth morphology, and environmental conditions to improve the accuracy of yield forecasts.
7. This study has important implications for climate-smart agriculture, particularly in optimizing nitrogen use and enhancing crop resilience to varying moisture conditions. In wet growing seasons, the risk of nitrogen saturation suggests the need for more conservative nitrogen management, such as reducing application rates or using split applications to improve nutrient-use efficiency and avoid over-fertilization. In contrast, during drought seasons, nitrogen may not be the primary limiting factor, and the focus should shift toward improving water management practices, such as irrigation scheduling, soil moisture conservation, and the use of drought-resistant varieties.

6. LIST OF PUBLICATIONS



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Candidate: Anteneh Agezew Melash
Doctoral School: Kálmán Kerpely Doctoral School
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List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (2)

1. **Melash, A. A.**, Vad, A., Bytyqi, B., Ábrahám, É. B.: Harnessing diversity in durum wheat (Triticum turgidum L.) to enhance climate resilience and micronutrient concentration through genetic and agronomic biofortification.
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2. **Melash, A. A.**, Ábrahám, É. B.: Integrated nutrient supply and varietal difference influence grain yield and yield related physio-morphological traits of durum wheat (Triticum turgidum L.) varieties under drought condition.
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Foreign language scientific articles in international journals (7)

3. **Melash, A. A.**, Bytyqi, B., Nyandi, M. S., Vad, A., Ábrahám, É. B.: Chlorophyll Meter: A precision agricultural decision-making tool for nutrient supply in durum wheat (Triticum turgidum L.) cultivation under drought conditions.
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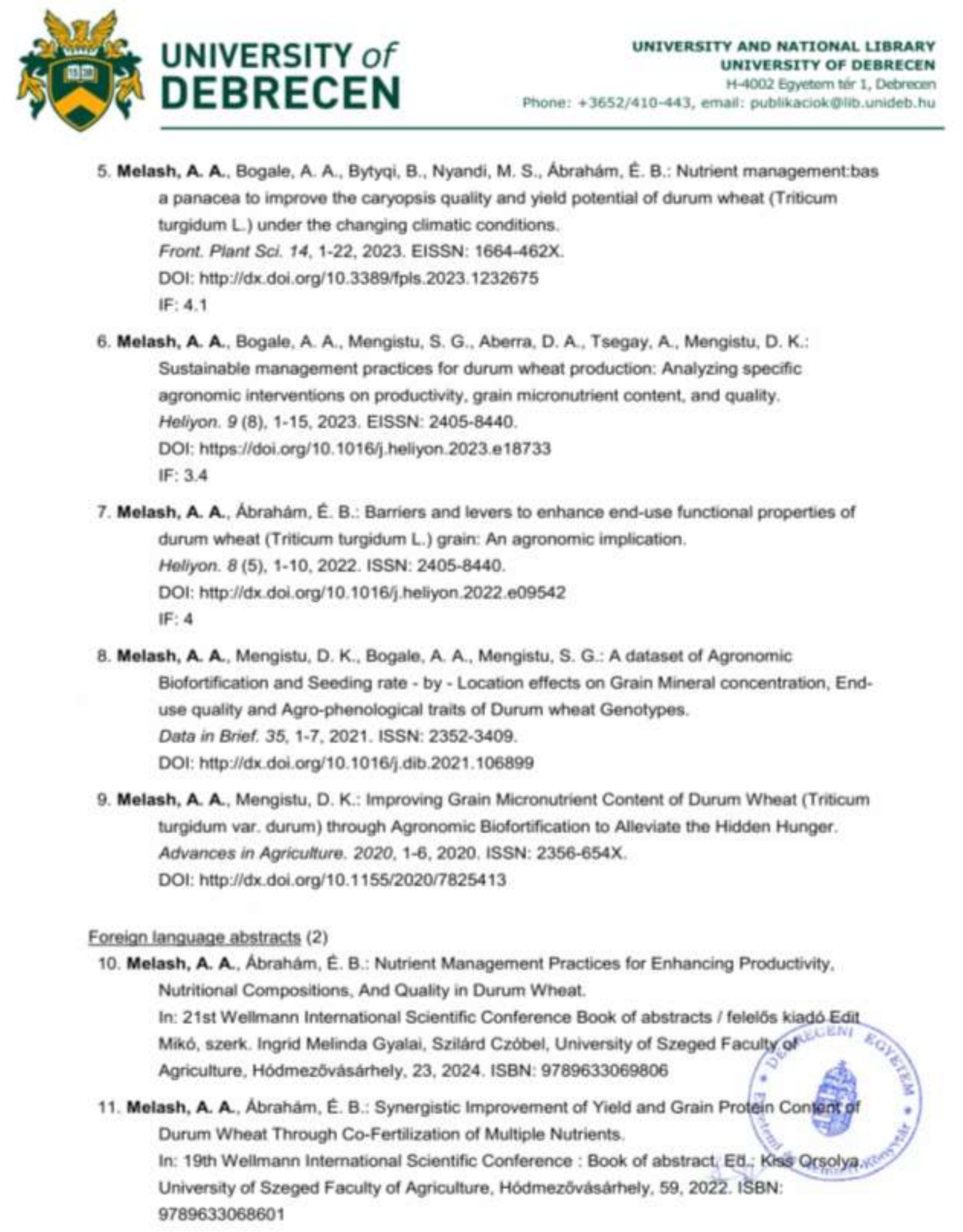

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11. **Melash, A. A.**, Ábrahám, É. B.: Synergistic Improvement of Yield and Grain Protein Content of Durum Wheat Through Co-Fertilization of Multiple Nutrients.
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List of other publications

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12. Kutasy, E., Diósi, G., Bódi, E., Nagy, P. T., **Melash, A. A.**, Forgács, F., Virág, I. C., Vad, A., Bytyqi, B., Buday, T., Csajbók, J.: Changes in plant and grain quality of winter oat (Avena sativa L.) varieties in response to silicon and sulphur foliar fertilisation under abiotic stress conditions.
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