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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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GROWTH, YIELD AND GRAIN QUALITATIVE TRAITS OF DURUM
WHEAT (*Triticum turgidum* L.) VARIETIES**

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LIST OF ABBREVIATIONS

BT	Booting Stage
CCD	Chlorophyll Content Dynamics
CV	Coefficient of Variation (%)
FS	Flowering Stage
GCI	Green Chlorophyll Index
GenStat	General Statistics
GPC	Grain Protein Content
GY	Grain Yield (kg ha ⁻¹)
HS	Heading Stage
LAI	Leaf Area Index
LDG	Lodging (%)
LSD	Least Significant Difference
N	Nitrogen
NDVI	Normalized Difference Vegetation Index
NIR	Near infrared
NUE	Nutrient Use Efficiency
PCA	Principal Component Analysis
PH	Plant Height (cm)
ROS	Reactive Oxygen Species
SAVI	Soil Adjusted Vegetation Index
SE	Stem elongation stage
SPAD	Soil Plant Analysis Development
SPD	Spike Density (m ²)
SPL	Spike Length (cm)
S	Sulphur
Z	Zinc
MV	Martonvásár
GK	Gabonakutató

1. INTRODUCTION

1.1. Background and Rationale

Durum wheat ($2n = 28$, AABB, *Triticum turgidum* var. *durum*) is a widely cultivated free-threshing allotetraploid wheat, accounting for approximately 5% of global wheat (*Triticum* spp.) production (Alemu et al., 2020). Known for its distinctive storage proteins, it plays a key role in producing pasta, couscous, and bread (Dimitrios, 2023). In Ethiopia, it is central to traditional dishes such as defo dabo, injera, and porridge (Mulugeta et al., 2024). However, despite its economic and nutritional importance, only 13% of the world's arable land is suitable for its production, and climate change is expected to shrink this area by 19% by mid-century and 48% by the end of the century (Ceglar et al., 2021). These significant reductions in arable land will likely result in reduced yields and compromised quality, as the environmental changes associated with climate change can adversely affect both the stability and nutritional value of durum wheat (Ceglar et al., 2021). The combination of diminishing suitable land, climate variability, and the need to feed an increasing global population raises urgent questions about the future of durum wheat production. This confluence of factors necessitates innovative agronomic solutions that can balance the need for increased production with the environmental realities facing modern agriculture.

The global demand for major grains, particularly wheat, is projected to surge by 70% by 2050, driven primarily by rapid population growth and the urgent need to ensure food security worldwide (Tilman et al., 2011). This escalating demand necessitates increased nitrogen input, which unfortunately amplifies nitrous oxide emissions, further contributing to climate change (Kumar and Bordoloi, 2024). This scenario presents a dual challenge: while agricultural productivity must rise to satisfy food requirements, the environmental footprint of agriculture must simultaneously decrease to ensure sustainability (Gan et al., 2014). The current agricultural practices are often characterized by an overreliance on intensive farming methods, inadequate irrigation systems, and monotonous cropping patterns, combined with excessive use of NPK fertilizers have led to significant nutrient deficits in soils (Zhao et al., 2020; Bisht and Chauhan, 2020). These nutrient imbalances are particularly pronounced in wheat-growing regions, where it is estimated that up to 50% of cultivated areas face substantial deficiencies in critical micronutrients, such as zinc and sulphur (Zhao et al., 2020; Feinberg et al., 2021;

Antošovský et al., 2024). Addressing these deficiencies requires adopting more balanced, targeted, and integrated fertilization strategies that are essential for sustaining crop productivity and enhancing long-term soil health. However, despite the pressing need for such approaches, much of the existing research has predominantly focused on the effects of single-element fertilizers, neglecting the potential benefits of the combined application of nitrogen, zinc, and sulphur (Shehzadi et al., 2024).

The pursuit of increasing crop yields and closing the gap between actual and attainable yields is fundamental to meeting the global demand for food (Penuelas et al., 2023). This can be achieved through the appropriate use of fertilizers and the efficient management of nutrients, both of which are essential for enhancing agricultural productivity and ensuring global food security (Stewart and Roberts, 2012). However, the environmental limits of fertilizer use are becoming increasingly apparent. The maximum sustainable application of nitrogen (N) fertilizers to prevent severe eutrophication of aquatic ecosystems is estimated at around 62 Tg N per year, yet current usage exceeds this threshold by at least threefold, causing significant ecological damage (Penuelas et al., 2023). This rising demand for nitrogen will necessitate proportional increases in phosphorus (P) and potassium (K) fertilizers to maintain balanced nutrient applications, placing additional pressure on global fertilizer markets and worsening food security challenges, particularly in low-income regions where fertilizer access is limited (Obersteiner et al., 2013). The situation is further complicated by rising global population and income levels, which will increase demand for food and agricultural products. By 2050, it is estimated that the environmental impacts of food production could rise by 50–90%, pushing agriculture's ecological footprint beyond safe planetary boundaries. This would create an unsustainable strain on natural resources unless there are significant technological innovations and concerted mitigation measures to reduce nutrient losses and improve nutrient use efficiency (Chang et al., 2021).

Introducing regional nitrogen targets and prioritizing supply-side measures, such as improving nitrogen use efficiency (NUE), are more crucial for ensuring food security than demand-side interventions (Chang et al., 2021). The enhancement of nutrient use efficiency, alongside the application of nitrogen fertilizers, forms a cornerstone of agronomic strategies aimed at improving grain yield, protein content, and the overall nutritional composition of crops (Xiong et al., 2015). However, achieving sustainable

improvements in crop productivity requires addressing several interconnected issues, such as managing the inherent genetic variability within crop populations, which influences how different varieties respond to nutrient inputs, and understanding genotype-environment interactions is essential for optimizing crop performance across diverse and changing growing conditions (Aga et al., 2024).

In addition to these biological and environmental complexities, the excessive use of nitrogen fertilizers has led to severe environmental consequences, including nitrate leaching into groundwater, contamination of water bodies, and increased greenhouse gas emissions. These environmental impacts are not only detrimental to ecosystem health but also pose significant challenges to human health and contribute to climate change, highlighting the urgent need to optimize NUE in agricultural systems. However, while improving NUE is crucial, it cannot be viewed as a standalone solution to the growing global food crisis. The rising demand for food due to population growth, estimated to reach 9.7 billion by 2050, requires a more holistic approach that integrates NUE with other critical agricultural innovations (Mustafa et al., 2022). A comprehensive strategy is needed, one that combines improvements in nitrogen efficiency with enhanced nutrient management practices, precision agriculture, advanced crop breeding techniques, and the promotion of sustainable agronomic practices.

The quest for optimal nitrogen application in durum wheat reveals a paradox in modern agriculture. Increased nitrogen rates can reduce, enhance, or have no effect on grain yield (Assefa et al., 2023; Chen et al., 2023), highlighting the lack of a universal nitrogen model. This variability calls for a refined approach that tailors nitrogen management to local conditions while emphasizing sustainability. The inconsistency in nitrogen response stems from complex genotype-by-environment interactions, study methodologies, soil types, irrigation, and application timing (Melash et al., 2023). These factors complicate drawing definitive recommendations, making a multi-factorial approach essential. Integrating genetic traits, environmental conditions, and precision agriculture is key to optimizing nitrogen use efficiency, improving yield and quality, and minimizing environmental impacts (Zhang et al., 2023). Nitrogen fertilization timing and rate significantly affect crop productivity, with moisture availability modulating these effects (de Lima et al., 2021; Li et al., 2022). High nitrogen during wet seasons reduces yield, nitrogen use efficiency (NUE), and flour quality, while promoting excessive vegetative

growth and increasing lodging risk (Li et al., 2022). In dry seasons, high nitrogen levels promote vegetative growth at the expense of reproductive development, leading to haying off—premature drying and senescence—that exacerbates water stress and reduces yield and quality (Li et al., 2022). Excessive nitrogen during drought periods diverts energy from grain-filling, lowering yields and nutritional quality (Van Herwaarden et al., 1998). This misallocation of resources highlights the need for optimized nitrogen management strategies, particularly in arid environments (Ghimire et al., 2021).

Agronomic interventions, such as the foliar application of zinc and sulphur-containing fertilizers, offer a viable strategy to address challenges in nitrogen utilization, improve grain quality, and mitigate the negative effects of immoderate nitrogen application and nitrogen loss (Mustafa et al., 2022). Zinc plays a crucial role in plant metabolic processes and protein synthesis, while sulphur is essential for amino acid formation and nitrogen metabolism (Suganya et al., 2020; Yu et al., 2018). The interaction between these nutrients and nitrogen, however, remains insufficiently studied, particularly across varying environmental conditions and cropping seasons. Integrated agronomic approaches are essential for not only increasing grain yield but also improving the nutritional and commercial value of crops. Exogenous applications of nutrients such as sulfur and zinc, whether applied individually or in combination with nitrogen, have demonstrated significant benefits in enhancing nitrogen use efficiency, grain yield, and protein content in durum wheat (Roa et al., 2024; Melash et al., 2023). However, limitations in sulfur availability, particularly in water-limited environments, present a considerable constraint on growth and yield potential (Usmani et al., 2020).

Water stress not only reduces carbon dioxide (CO₂) fixation but also disrupts the flux of sulfate into cysteine, a key amino acid essential for protein synthesis (Ahmad et al., 2016). Consequently, inadequate sulfur fertilization can limit wheat's yield potential and lead to inefficient nutrient utilization (Yu et al., 2018). The interaction between nitrogen and sulfur is particularly critical for effective protein synthesis; a deficiency in one nutrient exacerbates the deficiency of the other, resulting in compounded negative effects on growth and overall productivity crops (Wilson et al., 2020; Tao et al., 2018). Sulfur deficiency can significantly reduce nitrogen use efficiency, while nitrogen deficiency diminishes sulfur use efficiency (Lee et al., 2016). These interactions emphasize the importance of maintaining a balanced nitrogen-to-sulfur ratio to optimize both yield and

grain quality, underlining the need to investigate sulfur's role in nitrogen fertilization strategies (Klikocka et al., 2016; Carciochi et al., 2020; Jaenisch et al., 2020). Therefore, an integrated nutrient management approach, which considers both synergistic and antagonistic nutrient interactions, is essential for developing high-yielding, nutritionally dense durum wheat grain.

Integrated agronomic approaches are essential for addressing the dual challenge of enhancing both grain yield and nutritional quality. As global food demand continues to rise, there is an urgent need for sustainable agricultural practices that not only boost production but also improve the nutritional profile of food crops. This can be achieved through strategies focused on biofortification to increase zinc levels in durum wheat, optimizing nutrient management to improve overall nutrient use efficiency, and developing crop varieties with higher zinc content and lower phytate levels. Recent studies have shown that applying zinc-containing fertilizers alongside nitrogen significantly enhances the nutritional composition of durum wheat while reducing the concentration of phytic acid, which impairs zinc bioavailability (Akca and Taban, 2024). This benefit is further amplified when zinc fertilizers are combined with sulphur fertilizers, which not only improve grain yield but also increase zinc content.

The observed variability in yield, grain quality, and nutritional composition among durum wheat varieties under different agronomic practices highlights the need for a focused investigation into the specific constraints affecting production. This research aims to systematically evaluate these factors, with the goal of developing optimized nutrient management practices that enhance both yield and nutritional quality. The research further seeks to provide actionable insights into effective agronomic practices for durum wheat by refining strategies such as identifying optimal nitrogen application rates and integrating supplemental zinc and sulphur fertilization. These advancements will not only improve productivity for durum wheat producers but also offer science-based solutions that promote sustainable crop production, benefiting the broader agricultural sector. Beyond increasing yields and improving nutritional outcomes, this research will support the development of resilient, high-yielding varieties that meet market demands for both quality and sustainability. The knowledge gained will be crucial for minimizing the environmental impact of intensive agriculture, thus contributing to long-term food security in the face of a changing climate. Ultimately, this research aligns with the broader

goal of enhancing agricultural productivity while reinforcing the importance of sustainability in modern farming practices.

1.2. Objectives

The grain yield, commercial quality traits, and mineral concentration of durum wheat are significantly influenced by the complex interaction between genetic factors, fertilizer management, and environmental conditions. While the effects of climate change on grain yield have been widely studied, its impacts on the nutritional profile of durum wheat—particularly grain protein content—remain underexplored, despite their critical importance for food security. This research seeks to comprehensively examine the relationships among grain yield, storage protein composition, mineral concentration, and nitrogen fertilization within the context of current climate change scenarios. Advancing durum wheat production requires a scientific evaluation of nutrient supply, with a particular focus on nitrogen, zinc, and sulfur. These nutrients are not only crucial for enhancing grain yield and quality but also for promoting plant growth and resilience to drought stress across diverse growing seasons. In a more specific context, the study was conducted to:

- a) Assess the yield, agronomic characteristics, commercial qualitative traits, and physiological responses of various durum wheat varieties, considering seasonal variations and intra-varietal differences.
- b) Evaluate the effects of foliarly applied zinc and sulfur fertilizers, along with soil-based nitrogen application rates, on enhancing grain yield, physiological responses, and the grain nutritional composition of durum wheat.
- c) Develop and assess agronomic biofortification strategies aimed at improving grain mineral concentration, protein content, and overall yield in durum wheat.
- d) Investigate the relationships between storage grain protein composition and grain yield, incorporating the influence of both genetic and environmental factors.
- e) Examine the impact of terminal drought stress on the agronomic, phenological, physiological, and grain quality traits of durum wheat varieties.

2. LITERATURE REVIEW

In recent years, crop productivity and food security have emerged as critical global concerns, driving intensified research into the complex interplay between environmental factors, nutrient supply, and crop performance. Durum wheat, a cornerstone of the global food supply, holds particular significance in regions where it serves as a primary source of nutrition and calories (Grosse-Heilmann et al., 2024). The challenges associated with improving durum wheat yield and quality have spurred extensive scientific investigations aimed at understanding the effects of external factors, such as nutrient availability and drought stress, on its growth, yield, and grain quality traits. Research has increasingly highlighted the critical role of key nutrients including nitrogen, zinc, and sulphur—in shaping the growth, development, and productivity of durum wheat. These nutrients are not only crucial for enhancing yield but also for enhancing the crop's nutritional value, making them central to strategies for achieving sustainable food production.

The processes of nutrient uptake and assimilation are fundamental not only to enhancing yield but also to determining the qualitative attributes of durum wheat grains. However, the escalating challenge of drought stress, intensified by shifting climate patterns, poses a significant threat to global agriculture, with durum wheat being particularly vulnerable. Water scarcity disrupts essential physiological and biochemical processes, leading to reduced growth, yield, and grain quality. Understanding the interaction between drought stress and nutrient availability is critical to addressing these challenges and developing resilient cultivation strategies. While existing studies provide valuable insights into the effects of nutrient supply and drought stress on durum wheat, the findings remain fragmented.

Integrating these perspectives and elucidates the intricate interactions between environmental factors and nutrient dynamics is still lacking. This dissertation aims to bridge these gaps by investigating the influence of nutrient supply and naturally occurring drought stress on the growth, yield, and grain qualitative traits of durum wheat varieties. The primary objective of this literature review is to consolidate existing knowledge, identify critical research gaps, and establish a strong foundation for the subsequent chapters of the dissertation. Additionally, it aims to contribute to the broader scientific discourse on sustainable durum wheat production, paving the way for the development of evidence-based agronomic strategies.

2.1. Botanical, Taxonomic, and Cytogenetic Classification of Durum Wheat

Triticum durum, widely recognized as a descendant of emmer wheat, displays several distinct morphological traits that differentiate it from other emmer-related species. It typically features a tough rachis, soft and loose glumes, and spikelets that contain two to four free-threshing grains. Compared to emmer, its heads are generally less laterally compressed. The species is primarily composed of spring and semi-winter types, predominantly with bearded (awned) heads, while winter and beardless forms are relatively rare (Bennici, 1986). Durum grains vary in color—white, amber, red, and rarely purple—and are characteristically long, narrow, hard, and translucent. These grains are the hardest among all wheat species. The outer glume is noted for a prominent single keel that extends from tip to base. Stems of durum wheat are generally tall and may be either solid or hollow with thick walls (Bennici, 1986).

Durum wheat (*Triticum turgidum ssp. durum*), a monocot of the Gramineae family and Triticeae tribe, is the second most important *Triticum* species after common wheat (*T. aestivum* L.) for commercial and dietary use. It is a mid-tall annual grass characterized by flat leaf blades and a terminal spike with perfect flowers (Bozzini, 1988). Semi-dwarf varieties also exist. It has a dual root system: seminal roots develop at germination, while adventitious roots emerge later from basal nodes to form the permanent root system. The cylindrical, erect stem is usually hollow but can be solid in some varieties (Clarke et al., 2002). Tillers arise from basal nodes, with a plant typically producing three in addition to the main shoot under normal field conditions (Bozzini, 1988).

Botanically, durum wheat is characterized by a robust and erect growth habit, typically reaching heights of 90 to 120 cm. The stems (culms) are composed of hollow internodes, and the leaves are long, linear, and alternate with prominent auricles and open sheaths. The reproductive structure is a terminal spike composed of spikelets borne alternately on a central rachis. Spikelets generally contain 2–5 florets, each enclosed by glumes and often bearing long awns, a characteristic feature of many durum wheat varieties (Shewry, 2009). Durum wheat is self-pollinating, with floral structures that facilitate limited outcrossing. Its grain is a hard, vitreous caryopsis rich in carotenoids and protein, contributing to its yellow color and firm texture ideal for semolina processing (Sissons, 2008).

Wheat species within the genus *Triticum* are classified into three main groups based on ploidy levels: diploids ($2n=14$), tetraploids ($2n=28$), and hexaploids ($2n=42$), each with a basic chromosome number of seven. Prior to the discovery of their chromosome counts, wheats were categorized morphologically into three historical groups: Einkorn (diploid), Emmer (tetraploid), and Dinkel (hexaploid), as first proposed by Schulz in 1913. These ploidy levels reflect significant differences in chromosome composition and genome structure (Bennici, 1986).

Cytogenetically, diploid wheats such as *Triticum monococcum* contain one genome (AA), tetraploid wheats like *T. dicoccum* and *T. durum* possess two sets of genomes (AABB), and hexaploids such as *T. aestivum* (common wheat) have three sets (AABBDD). These polyploid species are allopolyploids, meaning they originated through interspecific hybridization followed by chromosome doubling. In the allotetraploid group (AABB), each genome consists of homologous chromosomes, and for each pair in one genome, there is a partially homologous (homeologous) pair in the second genome. In allohexaploid species, this complexity increases to include three related sets of homeologous chromosomes (Bennici, 1986).

The concept of homeologous chromosomes is critical in understanding genome behaviour during cell division, particularly meiosis, where chromosome pairing determines fertility and genetic recombination. Kihara (1924) classified the three genomes involved in wheat evolution as A, B, and D, where the A genome was derived from *Triticum urartu*, the B genome is believed to be contributed by a species related to *Aegilops speltoides*, and the D genome originated from *Aegilops tauschii*. All tetraploid wheats, including *T. durum*, share the same AABB genome configuration. The wild tetraploid species *T. dicoccoides* (wild emmer) is believed to be the ancestral member of this group. Through spontaneous mutations, natural hybridization, and farmer-mediated selection, the domesticated tetraploid *T. dicoccum* emerged. Further selection and genetic changes led to the evolution of free-threshing tetraploid wheats, particularly *T. durum*, which is widely cultivated today for pasta and semolina production. This cytogenetic framework provides critical insight into the evolutionary relationships among wheat species, and underpins modern wheat breeding strategies by guiding the introgression of desirable traits across ploidy levels (Bennici, 1986).



Figure 1. Morphological variation in *Triticum durum* showing differences in awn structure, spike compactness, and kernel traits among botanical varieties (Lyapunova, 2017).

2.2. Agro-Ecological Importance and Global Relevance of Durum Wheat

2.2.1. Global Distribution and Production Trends of Durum Wheat

Durum wheat (*Triticum turgidum* L. ssp. *durum*), the 10th most widely cultivated cereal globally, yields around 38 million tons annually (Xynias et al., 2020). It is predominantly grown in the Mediterranean region, which contributes approximately 75% of worldwide production (Broccanello et al., 2023). The global annual output of durum wheat fluctuates between 35 and 40 million tons, making up about 7% of total wheat production (Grosse-Heilmann et al., 2024; Xynias et al., 2020). This proportion has decreased since the 19th century when durum wheat represented about 14% to 16% of global wheat production (Martínez-Moreno et al., 2022). Canada is the leading producer of durum wheat, with an annual yield of 5.2 million tons, followed by Italy and Turkey, which produce 4.3 and 3.7 million tons, respectively.

Globally, durum wheat is cultivated on approximately 18 million hectares, accounting for 8%–10% of the total wheat-growing area (De Vita and Taranto, 2019). Key production areas include the Mediterranean Basin, North American Great Plains, and parts of West and Central Asia. Canada, Kazakhstan, Algeria, Italy, and Turkey are the largest producers, while smaller areas of cultivation are found in Mexico and Australia (Ceglar et al., 2021; Mccallum et al., 2019; De Vita and Taranto, 2019). In the European Union, Italy leads production with an average of 4.26 million tons annually from 1.28 million hectares over the past decade. France follows with 1.89 million tons (0.37 million hectares), Greece with 1.07 million tons (0.37 million hectares), and Spain with 0.98 million tons (0.38 million hectares) (Melash and Ábrahám, 2022).

In Eastern Africa, Ethiopia is the leading producer of durum wheat, with approximately 0.6 million hectares under cultivation (Tidiane et al., 2019). The country is also considered a primary center of genetic diversity for durum wheat (Mulugeta et al., 2024). Historically, durum wheat accounted for 60–70% of Ethiopia's total wheat-growing area, with production heavily reliant on traditional landraces. However, improved durum wheat varieties have only made up about 10% of this area, reflecting limited adoption despite their potential for higher yields (Hodson et al., 2020). The large-scale introduction of high-yielding, semi-dwarf bread wheat varieties has led to a reduction in durum wheat cultivation, as farmers have shifted to bread wheat due to its higher productivity, adaptability to modern agronomic practices, and greater economic benefits (Hodson et

al., 2020). Consequently, Ethiopia’s pasta and macaroni industries face shortages of locally produced high-quality durum wheat, forcing them to rely on imports. Each year, the country imports approximately 1.3 million tons of wheat and pasta, leading to significant foreign exchange costs (Melash et al., 2019). This highlights the considerable gap between the supply and demand for durum wheat, despite Ethiopia’s role as a genetic hotspot for the crop.

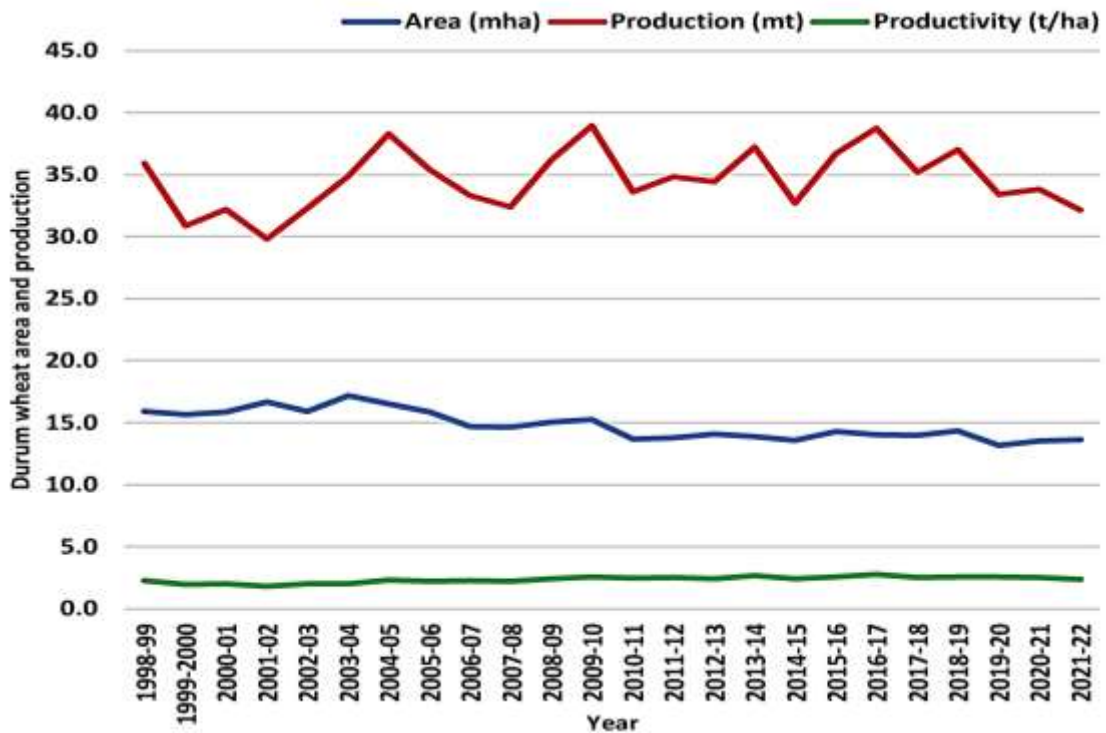


Figure 2. Global durum wheat cultivation area, grain production, and productivity trends from 1998 to 2022 (Blanco, 2024).

2.2.2. The Climatic Requirement and Adaptability

Durum wheat is widely recognized for its adaptability to semi-arid environments, demonstrating resilience to climatic stresses such as high temperatures, low rainfall, and extended drought periods (Grosse-Heilmann et al., 2024). This adaptability makes it particularly suited for regions where climate variability presents a major challenge to agricultural productivity. In the Mediterranean basin, for instance, durum wheat is typically cultivated as winter wheat, leveraging the mild, wet winters to establish the crop before the onset of summer drought. This seasonal adaptation helps the plant to avoid the more extreme temperatures and moisture deficits that occur later in the growing season (Sieber et al., 2014). In contrast, in northern regions characterized by colder and longer

winters, durum wheat is sown in the spring, when the risk of frost damage has subsided, with harvesting typically occurring in early autumn (Sieber et al., 2014). The spring-sown varieties must complete their growth cycle within a shorter window, often in cooler conditions, which can influence their physiological and developmental processes compared to winter-sown varieties. These regional differences in sowing times reflect the crop's flexibility and its capacity to adapt to diverse agro-climatic conditions.

The impact of climate change on the production and quality of durum wheat remains a significant concern for agricultural sustainability. Regions with Mediterranean-like climates, where durum wheat is predominantly grown, are particularly vulnerable to the effects of climate change. These areas are experiencing faster warming compared to other parts of the world (Diffenbaugh and Giorgi, 2012), and are also facing altered precipitation patterns and an increase in extreme weather events. These factors pose considerable risks to the resilience of both natural ecosystems and agricultural systems (Brogli et al., 2019). Addressing these challenges requires the development of adaptive strategies to maintain the productivity and quality of durum wheat in a rapidly changing climate.

In temperate climates, the selection between autumn-sown (winter) and spring-sown (spring) durum wheat varieties is critical due to their distinct growth requirements and environmental tolerances. Winter durum wheat varieties necessitate a cold exposure period (vernalization) to transition from vegetative to reproductive stages, enabling them to endure freezing temperatures during winter. These varieties require temperatures below 5°C for several weeks to effectively complete vernalization and initiate flowering in the spring. In contrast, spring durum wheat varieties have minimal to no vernalization requirements, allowing for sowing in spring after the risk of frost has diminished. These varieties are adapted to rapidly progress from sowing to maturity in the warmer temperatures of the growing season, making them suitable for regions with harsh winters or where early sowing is unfeasible (Koppensteiner et al., 2022).

2.2.3. Industrial and Economic Significance

Durum wheat, renowned for its unique storage proteins, is primarily used in the production of pasta, couscous, and bread (Ceglar et al., 2021). When durum wheat flour is hydrated and mixed into dough, these proteins form a viscoelastic network known as gluten, essential for providing the structure, elasticity, and texture necessary for shaping, raising, and baking various products (Koga et al., 2015). There has been growing market interest in grain protein content, in recent years, with farmers earning premium prices for durum wheat containing more than 13% protein. This ensures that the resulting semolina contains approximately 12% protein, a key attribute for meeting the quality standards of various end products (Melash and Abraham, 2022). The quest to enhance durum wheat's commercial grain quality, nutritional profile, and yield is increasingly critical in response to rising climate change, global food demands and evolving market preferences (Blanco, 2024). The increasing market emphasis on durum wheat with higher protein content reflects the broader trend towards optimizing crop characteristics for enhanced commercial value and yield. Thus, ongoing efforts to improve durum wheat's agronomic traits are essential to meet both consumer expectations and the growing demand for high-quality durum wheat in the global market.

Grain Hardness and Semolina yield: are determined by the structural organization of components within the endosperm cells. This quality reflects the grain's resistance to fracturing forces and the energy needed to process it into finer particles, such as semolina or refined flour. Durum wheat, in particular, has a harder endosperm than other wheat species, including hard-grained common wheat. This feature plays a crucial role in milling characteristics, such as the water absorption capacity of semolina and the quality of the resulting dough (Melash and Abraham, 2022). In milling industries, the primary concern is milling yield, which is the percentage of grain converted into semolina of acceptable purity while minimizing flour production. Since semolina typically has a higher market value, this factor is essential for profitability (Kadkol and Sissons, 2016). However, high milling extraction rates may lead to an increase in ash content (0.9–1.1% on a dry weight basis) due to contamination from bran, which can reduce the brightness and yellowness of the semolina (Kadkol and Sissons, 2016). Conversely, durum wheat grown in low-nitrogen environments has shown reduced kernel protein content and semolina yield, along with a higher starch content. These changes are likely associated

with the rapid breakdown of starchy kernels into fine flour particles during milling (Sissons et al., 2000).

Storage proteins: Storage Proteins: Unlike bread wheat (*Triticum aestivum*), durum wheat (*Triticum turgidum*) is distinguished by its higher grain storage protein content, extreme grain hardness, intense yellow pigmentation, and superior milling characteristics, which make it ideal for pasta production and contribute to its excellent cooking qualities (Nilusha et al., 2019). For durum wheat, maintaining a grain protein content above 13% (on an 11% moisture basis) is crucial to achieve approximately 12% protein in milled semolina, which is essential for ensuring a desirable texture in cooked pasta (Kadkol and Sissons, 2016). Research indicates that dry pasta made from semolina with higher protein levels (>12%) exhibits greater physical strength and elasticity compared to pasta produced from lower-protein semolina (Kadkol and Sissons, 2016). High grain protein content enhances the ability of pasta to swell during cooking, minimizes cooking losses, and ensures firmness even with overcooking, while reducing stickiness. In the bread-baking industry, high-protein wheat flour is preferred for its ability to improve loaf volume, water absorption, and overall shelf life of the bread (Melash and Eva, 2022). These characteristics highlight the importance of storage proteins in determining the quality and functionality of durum wheat-based food products.

Gluten Strength and Quality: The semolina derived from high-protein durum wheat, particularly extra-strong varieties, is believed to contribute to firmer pasta (Cecchini et al., 2021). Gluten plays a crucial role in dough rheology, where its absence leads to a noticeable reduction in both cohesion and elasticity. Gluten-free dough, in contrast to wheat dough, lacks the structural integrity needed to trap gases during proofing, resulting in a less stable product (Cappelli et al., 2020). In wheat flour, gluten forms after starch, non-starchy polysaccharides, and water-soluble components are removed. It consists of glutenins, which are alcohol-insoluble, and gliadins, which are alcohol-soluble proteins (Tran et al., 2020). These proteins combine to form a cohesive, viscoelastic network that enables the dough to maintain its structure and volume during baking. However, for individuals with celiac disease, the absence of gluten severely impacts the dough's ability to hold shape and produce the characteristic texture of wheat-based products. Gluten-free breads, for instance, often suffer from lower volume, crumbly texture, inferior flavor, and quicker staling compared to traditional wheat bread (Bourekoua et al., 2017). These

differences underline the essential role gluten plays in the quality of both pasta and bakery products, influencing factors like texture, gas retention, and overall product performance.

2.3. Nutrient Management Strategies for Sustainable Durum Wheat Production

Recent agronomic research has highlighted nutrient management technologies as valuable tools for boosting crop yields and enhancing grain quality in response to the challenges of climate change (Sapkota et al., 2021). Climate-induced changes are shifting suitable growing areas, decreasing grain yields, and impacting the nutritional quality of grains. These shifts underscore the importance of developing comprehensive nutrient management strategies throughout the entire food supply chain to address the evolving challenges and ensure sustainable agricultural productivity. While studies highlight their potential as agronomic solutions, it is crucial to recognize that optimizing fertilizer applications alone may not suffice in mitigating the multifaceted influences of climate change on durum wheat productivity. Instead, effective fertilizer management should be integrated into broader, climate-smart agricultural frameworks, encompassing sustainable practices such as improved irrigation techniques, crop rotation strategies, and soil conservation measures. This holistic approach not only aims to enhance resilience against environmental stresses but also seeks to optimize resource use efficiency, thereby fostering sustainable agricultural production systems capable of meeting future food security demands.

Nutrient management is increasingly seen as a key strategy to mitigate the adverse effects of climate change on durum wheat production (Melash and Abraham, 2022). The adoption of advanced site-specific technologies enables precise nutrient application, factoring in variables such as timing, rates, and placement. This targeted approach not only improves durum wheat yields but also reduces its environmental impact (Kizilgeci et al., 2021). Studies indicate that precision nutrient management not only enhances grain yield and protein content but also optimizes nutrient and water use, contributing to a reduction in greenhouse gas emissions (Sadhukhan et al., 2023).

In broader agricultural practices, adopting expert-recommended nutrient management strategies has yielded significant benefits. This approach has resulted in substantial reductions in nitrogen fertilizer use and associated CO₂ equivalent emissions annually, alongside increased crop yields for staples like wheat and rice (Sapkota et al., 2021). This reduction reflects enhanced precision and efficiency in nitrogen use, minimizing wastage

and mitigating environmental impacts. Strategically managing nitrogen fertilizer holds significant potential for enhancing durum wheat yield and resilience to stressors. Nitrogen supports crucial functions such as maintaining leaf water potential, supporting photosynthesis, and bolstering antioxidative defenses, all of which contribute to improved performance of the crop (Abid et al., 2016). In addressing challenges posed by drought stress, integrating nitrogen, sulphur, sludge, and zinc-containing fertilizers has proven effective in alleviating abiotic stressors (Boudjabi et al., 2015; Ma et al., 2017). Incorporating these inputs into durum wheat cultivation systems can optimize nutrient availability, enhance plant health, and fortify resilience against climate variability.

The recent findings corroborate the efficacy of integrating farmyard manure and silicon-based fertilizers as synergistic strategies to elevate growth dynamics, amplify grain yield, augment nutrient assimilation, refine crop quality attributes, and optimize nitrogen utilization efficiencies in durum wheat (Naik et al., 2022). These integrated approaches highlight the crucial role of nutrient management in mitigating the negative impacts of climate change on agricultural production while advancing sustainable farming practices. Such holistic approaches resonate with global initiatives aimed at fortifying agricultural resilience and productivity in the context of evolving climate challenges. Harmonizing the application of organic inputs like farmyard manure with the targeted supplementation of silicon-based fertilizers, can potentially enhance soil health, bolster plant vigour, and improve overall crop performance. This integrated approach not only helps secure food supplies in the face of climate challenges but also promotes environmental sustainability by reducing greenhouse gas emissions and decreasing dependence on synthetic fertilizers. In essence, the incorporation of farmyard manure and silicon-based fertilizers represents a forward-thinking strategy in nutrient management, contributing to the global goals of building resilient agricultural systems that ensure food security and protect natural resources for the future.

2.3.1. Nitrogen Dynamics in Plant Systems: Sources, Forms, and Uptake Mechanisms

Nitrogen (N) is a crucial inorganic macronutrient required in substantial amounts for plant growth, development, biomass production, and grain yield. It regulates key metabolic processes within plants (Naz et al., 2019). As an essential component of amino acids, proteins, nucleic acids, lipids, and chlorophyll, nitrogen also influences numerous

nitrogen-containing metabolites (Akhtar et al., 2024). The physiological responses of plants to nitrogen fertilization are critical in determining both the yield and qualitative traits (Akhtar et al., 2024). Plants primarily absorb nitrogen in the form of nitrate (NO_3^-), which is then converted into amino acids through enzymes such as, nitrate reductase (NR), glutamine synthetase (GS), glutamate synthase (GOGAT), and glutamate dehydrogenase (GDH) (Tang et al., 2019). Amino acids serve as the primary substrate for protein synthesis in plant cells, eventually contributing to plant biomass through processes of classification, modification, transport, and storage (Khan et al., 2016). The efficient assimilation and utilization of nitrogen are therefore fundamental to promoting overall plant productivity and ensuring robust crop yields.

Nitrogen exists in both inorganic and organic forms, each playing a crucial role in plant nutrition. The primary inorganic forms of nitrogen include ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-), while organic nitrogen is present in compounds such as proteins, amino acids, nucleotides, urea and nucleic acids (Akhtar et al., 2024). Organic nitrogen must be converted into NH_4^+ through a process known as nitrogen mineralization before plants can utilize it. Soil microorganisms also play a critical role in converting different nitrogen forms, particularly transforming organic nitrogen into NO_3^- or NH_4^+ , making it available for plant uptake (Akhtar et al., 2024). Organic nitrogen sources, such as animal wastes and crop residues, are rich in nitrogen and contribute to soil fertility. Additionally, legume crops are often utilized for their nitrogen-fixing abilities and as green manure, enriching the soil with nitrogen through symbiotic relationships with nitrogen-fixing bacteria. However, nitrogen from organic sources must typically be converted into NO_3^- under specific conditions, such as anaerobic environments, before it can be utilized by crops. The nitrogen cycle is characterized by several major processes, including denitrification, where NO_3^- is used to oxidize organic carbon, resulting in the production of nitrogen gas (N_2); the oxidation of NH_4^+ to NO_3^- by chemosynthetic bacteria; the assimilation of NH_4^+ by plants; nitrogen fixation by bacteria; and the excretion of NH_4^+ by heterotrophic organisms (Dodds & Whiles, 2020). These fluxes are essential for maintaining nitrogen balance in ecosystems, supporting both crop productivity and environmental sustainability.

2.3.2. Balancing Nitrogen for Optimal Productivity and Sustainability

The challenge of nitrogen application in agriculture is a complex issue that requires a delicate balance between enhancing crop productivity and protecting ecosystems. Nitrogen is a vital nutrient for crop growth, and its use as fertilizer is a common practice to boost grain yield. Nitrogen is an essential nutrient for plant growth, and its application as fertilizer is a common practice aimed at improving crop yields. However, excessive or mismanaged nitrogen use not only reduces NUE but also contributes to serious environmental consequences, such as nitrate leaching into water bodies and the release of nitrous oxide (N₂O), a potent greenhouse gas that exacerbates climate change (Wang et al., 2023). Addressing the dichotomy of nitrogen application requires a holistic and integrated approach that considers both agricultural productivity and environmental conservation. Effective practices include precise application methods, such as split or variable-rate fertilization, which can optimize nitrogen use efficiency and minimize environmental losses.

A major challenge in modern agricultural practices is the simultaneous improvement of both grain yield and quality, particularly regarding protein content, under varying nitrogen application levels. This issue stems primarily from the inverse relationship observed between grain yield and protein content. As grain yield increases, grain protein content tends to decrease, a phenomenon often referred to as the dilution effect (Geyer et al., 2022). This intricate balance poses a substantial dilemma, necessitating strategic approaches to optimize both yield and protein content in a sustainable manner. Agronomic approaches, including the strategic application of nitrogen fertilizer in multiple doses at appropriate timings, have shown promise in mitigating the adverse impact on grain protein content, gluten content, and related characteristics (Melash, 2019). Nonetheless, it's notable that the quantity of nitrogen fertilizer significantly affects grain quality traits more profoundly than it does grain yield (Neil et al., 2012). This suggests that achieving desirable grain protein content might necessitate a notably higher total nitrogen application than what would be typically required solely for enhancing yield and yield attributed metrics.

High doses of nitrogen fertilization often lead to significant changes in protein content and associated quality traits (Eser et al., 2020; Shoumin et al., 2020). These changes may result from the influence of nitrogen on gene expression levels involved in the production of primary grain storage proteins (Yu et al., 2017). Alterations in gene expression can

modify the composition and abundance of storage proteins, ultimately impacting the grain's functional properties for different end-uses. Thus, understanding the interaction between nitrogen fertilization, gene expression, and protein composition is crucial for optimizing grain quality and end-use functionality.

The relationship between wheat response to increasing nitrogen application doses and the enhancement of grain storage proteins appears to be erratic across studies. While some studies have indicated that applying nitrogen fertilizer at higher rates has only a modest effect on gluten strength, gluten content, protein polymerization, and assembly (Gagliardi et al., 2020), other studies report that nitrogen application does not significantly affect grain protein content (Ghimire et al., 2021). These disparities in response could stem from several factors, including the genetic variability in how nitrogen is allocated to different storage protein fractions and the sensitivity of these responses to the local pedoclimatic conditions of the growing areas. Additionally, when nutrient use efficiency is evaluated in terms of grain yield per unit of nitrogen input, it tends to decrease with higher N inputs (Hawkesford, 2012). This suggests that while increased nitrogen fertilization may lead to higher yields, the additional input does not necessarily translate into proportionate gains in grain yield, indicating diminishing returns in terms of nutrient utilization efficiency.

Applying nitrogen fertilizer at higher rates can enhance both grain yield and quality traits in wheat. However, it also poses risks, particularly in terms of foliar disease development. Managing nitrogen fertilization becomes crucial to maintain acceptable grain quality while minimizing the risk of disease. High nitrogen doses can increase the plant's susceptibility to fungal diseases by fostering an environment that supports greater biomass production, which in turn can provide a favourable habitat for pathogens (Devadas et al., 2014; Zhang et al., 2017). Moreover, nitrogen promotes the availability of compounds that are essential for the growth of disease-causing organisms (Hoffland et al., 2000). This highlights the importance of carefully managing nitrogen application to strike a balance between enhancing grain quality and minimizing disease susceptibility. Additionally, applying nitrogen fertilizer at enhanced rates can lead to an increase in leaf area index (Zhang et al., 2020). While this can potentially increase radiation interception and use efficiency, it may also prolong the maturity period due to the higher leaf area, impacting overall crop development (Zhang et al., 2020; Walters et al., 2007).

Augmenting nitrogen fertilization at high levels can also lead to a decrease in nitrogen use efficiency in crops (Hawkesford, 2014). This decline in efficiency is often accompanied by reductions in wheat yield and flour quality (Brisson et al., 2010). A key factor contributing to this decline is lodging, a phenomenon in which excessive nitrogen leads to excessive vegetative growth, making plants top-heavy and more susceptible to bending or breaking. Lodging not only compromises the structural integrity of the plants but also diminishes their photosynthetic capacity and creates conditions favourable for fungal and leaf disease development, further exacerbating the negative impact on crop health and yield (Acreche et al., 2011). While optimizing nitrogen fertilization can help mitigate the risk of lodging by reducing shoot weight depletion (Berry et al., 2002), wheat may still fail to fully express its genetic capacity for protein accumulation under these conditions (Yu et al., 2017).

Improving nutrient use efficiency in wheat offers substantial benefits, including increased grain yield, improved protein content, and reduced environmental impact. Optimizing fertilizer management through appropriate application timing and precise nutrient rates has been shown to enhance nitrogen utilization efficiency. The combined application of nitrogen and sulphur fertilizers throughout the crop's growth cycle has been particularly effective in improving nutrient uptake and assimilation (Salvagiotti et al., 2009). Additionally, strategies such as late-season nitrogen application and split fertilization have demonstrated positive effects on nitrogen use efficiency by increasing plant nitrogen uptake, ultimately leading to higher grain protein accumulation (Woolfolk et al., 2002; Ercoli et al., 2013). Research indicates that nitrogen absorption during the post-booting stage contributes more significantly to protein accumulation in grains than to yield enhancement (Davis et al., 2009). Furthermore, the practice of splitting nitrogen applications has been widely recognized as a crucial agronomic strategy for optimizing nutrient use efficiency, thereby improving both grain yield and protein concentration (Ercoli et al., 2013). However, the effectiveness of these strategies is highly dependent on the plant's developmental stage, as nitrogen assimilation at different growth phases influences protein deposition in the grain.

2.3.3. Adaptive Nitrogen Fertilization for Water-Scarce and Climate-Variable Systems

Innovations in agricultural practices, such as nitrogen-efficient crop varieties, and optimized fertilization techniques, are being developed to harness nitrogen's potential in drought-proofing agriculture while minimizing environmental impacts. Research has shown that under drought stress, plant water status is significantly affected, with a decline in relative water content (Ahluwalia et al., 2021). As a key component of chlorophyll and proteins, nitrogen plays a crucial role in improving crop productivity, particularly through its application as fertilizer (Ata-Ul-Karim et al., 2016). Nitrogen boosts photosynthesis in flag leaves, thereby increasing overall yield (Noor et al., 2023). Studies have indicated that nitrogen application during the vegetative phase can mitigate the adverse effects of drought stress by supporting high leaf water potential, enhancing photosynthetic activity, and strengthening antioxidative defenses (Abid et al., 2016). Nitrogen metabolism is crucial for plant health, particularly under drought conditions. Higher nitrogen content in leaves enhances stomatal sensitivity to drought stress, allowing plants to maintain higher photosynthetic capacity (Meng et al., 2016). However, drought stress often leads to decreased photosynthetic efficiency, which in turn reduces the activity of key nitrogen-metabolizing enzymes, such as glutamine synthetase (GS) and nitrate reductase (NR) (Akhtar et al., 2024).

The simultaneous occurrence of nitrogen deficiency and drought stress has a profound impact on wheat's physiological functions, as both factors are intricately linked (Abid et al., 2016). However, the influence of nitrogen on wheat during various stages of drought stress remains underexplored. Investigating how nitrogen interacts with drought conditions at different growth phases can provide essential information for developing wheat varieties with improved drought tolerance (Teixeira et al., 2014). A comprehensive analysis of how nitrogen deficiency and drought stress jointly affect wheat's morphology, physiological processes, and grain quality can enhance our understanding of durum wheat's performance under stress. Strengthening the drought resilience of critical crops is pivotal for sustainable agricultural practices, especially considering that droughts can significantly reduce crop yields (Seleiman et al., 2021). Drought stress leads to osmotic stress, hindering plant transpiration and limiting nitrogen uptake and its transport within the plant (Fahad et al., 2017). Consequently, root structure, plant physiological functions,

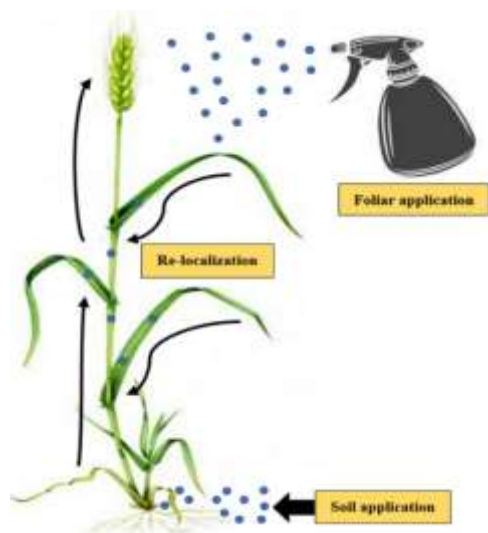
nutrient movement, and crop yield can all be severely impacted under these conditions (Ahanger et al., 2021; Hussain et al., 2018).

The absorption process of nitrogen in the soil is closely tied to water movement. Initially, nitrogen in the form of NH_4^+ or NO_3^- dissolves in water before being absorbed by plant roots and translocated to the aerial parts of the plant (Alet et al., 2012). However, drought stress significantly impairs the absorption of both NH_4^+ and NO_3^- . Research indicates that after root absorption, plants tend to assimilate a higher concentration of NH_4^+ compared to NO_3^- , which is absorbed in minimal amounts. This conversion process is facilitated by enzymes such as nitrite reductase (NiR) and nitrate reductase (NR), which convert NO_3^- to NH_4^+ in the roots (Akhtar et al., 2024). Moreover, drought stress affects the transcriptional abundance of genes and enzyme activities involved in nitrogen metabolism (Huang et al., 2018). Given the importance of nitrogen metabolism in plants, higher nitrogen content in leaves can increase stomatal sensitivity to drought stress while maintaining higher photosynthetic capacity (Meng et al., 2016). This relationship indicates the need for effective nitrogen management strategies that can enhance drought resilience and overall crop performance.

Various mineral elements, both essential and beneficial, are commonly used as soil or foliar fertilizers to counteract the negative impacts of abiotic stresses and to boost plant stress tolerance (Hasanuzzaman et al., 2017). The application of these nutrients is pivotal in enhancing plant resilience under challenging environmental conditions. During the rainy season, multiple cycles of wetting and drying in soils significantly alter the microbial population, which in turn regulates nitrogen (N) metabolic pathways (Liu et al., 2022). These changes in microbial communities can influence the availability of nitrogen in the soil, thereby affecting plant nutrient uptake and overall growth. Enhanced microbial activity during wetting and drying cycles can lead to improved nitrogen mineralization, which is vital for plant health and productivity. Consequently, integrating mineral fertilizers with effective soil management practices can optimize nutrient availability and bolster plant defenses against abiotic stresses (Akhtar et al., 2024).

2.3.4. Zinc Containing Fertilizer Application to Enhance Crop Resilience and Grain Quality

Modern wheat cultivation faces challenges due to the low bioavailability of micronutrients in the soil, making the exogenous application of essential elements necessary. This underscores the critical need to enhance soil fertility, as insufficient micronutrient concentrations can negatively impact grain mineral content. Wheat grain quality traits can be improved through agronomic biofortification, involving the application of micronutrient-rich fertilizers, or through genetic biofortification via breeding programs (Basso et al., 2010; Garg et al., 2018). Agronomic biofortification has emerged as an effective strategy to increase micronutrient concentrations, grain yield, and crop resilience against abiotic stresses (De Valença et al., 2017; Cakmak, 2018; Melash et al., 2019). This method involves applying micronutrient-based fertilizers to the soil or plant foliage, which effectively boosts the nutrient content in edible crop parts. It complements traditional breeding methods, offering a potential solution to micronutrient malnutrition by ensuring crops contain adequate nutrients (Melash and Dejene, 2020). When combined with breeding programs, biofortification provides a more comprehensive approach to addressing micronutrient deficiencies in staple crops. However, the success of fertilizer-based interventions is heavily influenced by the type of fertilizers used and their application methods. Fertilizer efficiency, solubility, uptake rates, and interactions with the process of applying micronutrient-rich appropriate fertilizer and its optimal application methods are key factors. Figure 3 illustrates the benefits of agronomic biofortification (Velt) to plant leaves (foliar application) to boost the



micronutrient content in the edible portions of food crops. The goal of this method is to enhance the nutritional quality of crops by increasing the levels of essential micronutrients, thereby helping to alleviate nutrient deficiencies in human diets (Singh et al., 2023).

Various zinc nutrient application sources, including EDTA-chelated zinc and zinc sulfate ($ZnSO_4$), have been recommended for wheat crops. However, foliar application of zinc sulfate has consistently been recognized as the most effective and cost-efficient method

compared to EDTA-chelated zinc (Cakmak and Kutman, 2018). This underscores the importance of fertilizer formulation in determining the bioavailability of micronutrients. The nutrient form and its interaction with environmental factors can significantly influence both grain yield and nutrient use efficiency (Rietra et al., 2015). Therefore, selecting the appropriate application method and fertilizer source is crucial to meet the nutrient requirements of crops, especially in durum wheat biofortification efforts. Foliar application of micronutrients generally leads to better nutrient uptake and allocation to edible plant parts, enhancing grain quality and yield more effectively than soil application (Lawson et al., 2015).

The application of foliar-based zinc and iron fertilizers at various developmental stages has been shown to improve grain zinc concentration, though the degree of enhancement varies depending on the absorption efficiency of different wheat varieties (Dhaliwal et al., 2013). Foliar zinc application has been found to be more effective than soil-based application in boosting grain zinc concentration in wheat (Ram et al., 2015). Agronomic biofortification is more effective when multiple application methods are used. For example, combining foliar and soil-based zinc applications results in increased grain zinc content, biomass yield, grain yield, protein content, and fodder quality (Khattak et al., 2015; Cakmak and Kutman, 2018). The effectiveness of this combined approach can be attributed to the complementary benefits each method offers: soil-based zinc fertilization enhances zinc bioavailability in the rhizosphere, while foliar application facilitates rapid translocation into storage organs by improving absorption efficiency (Dhaliwal et al., 2022). Agronomic biofortification has proven to be a practical method for improving grain mineral content, with grain zinc concentration increasing from 33.04 mg kg⁻¹ to 56.73 mg kg⁻¹ through this approach (Melash and Dejene, 2020). Studies have shown that using a combination of soil and foliar applications leads to greater improvements in grain micronutrient concentrations than using single application methods (Phattarakul et al., 2012; Cakmak, 2010).

Agronomic biofortification using zinc-containing fertilizers has proven to be more effective when combined with other essential nutrients. This synergistic approach enhances the bioavailability of zinc while also improving the overall nutrient uptake and utilization by crops. For example, combining zinc-containing fertilizers with NPK fertilizers resulted in significant increases in both high (38.8%) and low molecular weight (6.7%) glutenins (Stepien and Wojtkowiak, 2016). Another study demonstrated that

splitting nitrogen fertilizer applications at sowing and stem elongation stages, along with combined soil and foliar applications of zinc and iron-containing fertilizers, can be effective crop management strategies to improve grain protein content, as well as zinc and iron concentrations (Bal et al., 2018). Furthermore, foliar nitrogen application, in combination with both soil and foliar zinc applications, was found to be the most effective combination for achieving optimal grain protein content (Shahid et al., 2018).

Integrating zinc into agronomic practices has been shown to significantly improve the resilience of durum wheat against various environmental stresses (Ma et al., 2017). While foliar applications of zinc-containing fertilizers may not offer substantial benefits in the absence of drought stress, they have been found to boost grain yield by around 15% and enhance grain zinc concentration during drought conditions (Karim et al., 2012). In contrast, zinc deficiency in soils leads to a substantial reduction in grain yield, particularly during drought periods (Bagci et al., 2007). This underscores the importance of adequate zinc fertilization, as the combined impact of drought and zinc deficiency can negatively affect both grain yield and mineral content. The nutrient requirements of crops are closely tied to soil water availability, making adequate zinc fertilization especially crucial during drought conditions. Therefore, ensuring sufficient zinc levels in the soil, particularly during water-limited periods, is vital for maintaining crop productivity and improving the nutritional quality of durum wheat grains. This highlights the importance of incorporating zinc management strategies into agronomic practices to optimize yield and nutrient content in challenging environmental conditions.

The increased yield and grain zinc concentration resulting from the application of zinc-containing fertilizers can be attributed to zinc's essential role in detoxifying reactive oxygen species (ROS) and boosting antioxidant enzyme activity (Anik et al., 2023). Physiologically, zinc fertilization enhances photochemical reactions in the thylakoid membrane, improves electron transport through PSII, and increases the photosynthetic rate and chlorophyll content (Younes et al., 2016). However, the impact of zinc fertilization under varying levels of drought stress at different phenological stages of durum wheat remains unclear. Studying the effects of drought stress combined with different doses of zinc fertilization on both qualitative and quantitative agronomic traits is crucial for developing drought-tolerant durum wheat varieties. Thus, we recommend a comprehensive evaluation of the combined effects of zinc deficiency and drought stress on the morphological, physiological, and grain quality characteristics of durum wheat.

This approach would provide valuable insights and improve our understanding of durum wheat performance under stress conditions.

The need to achieve enhanced food security while preserving environmental sustainability is becoming increasingly urgent in the context of current climate change challenges. Zinc deficiency has been associated with decreased crop yields and reduced grain protein content, as zinc plays a vital role in enzyme synthesis related to nitrogen metabolism, a process crucial for protein production in plants (Melash et al., 2019). Climate change, marked by rising temperatures and erratic rainfall, presents substantial obstacles to crop growth and productivity. However, the use of zinc containing fertilizers has revealed potential in alleviating these challenges by improving nutrient availability and boosting key physiological processes, including the production of photosynthetic pigments, active oxygen scavenging, and the reduction of lipid peroxidation, particularly under drought conditions (Ma et al., 2017).

The interaction between zinc fertilization and drought stress alleviation is evident in zinc's ability to neutralize reactive oxygen species (ROS) and enhance antioxidant enzyme activity (Anik et al., 2023; Sofy, 2015). Studies have shown that zinc application significantly increases the activity of enzymes such as catalase, superoxide dismutase, peroxidase, and ascorbate peroxidase, with the most notable effects observed under drought conditions at 40% water holding capacity, a marker of water stress (Sattar et al., 2022). This suggests that zinc application strengthens the wheat plant's antioxidant defense mechanisms, improving its resilience to oxidative stress caused by limited water availability. Furthermore, the method of zinc application plays a critical role in determining its effectiveness in enhancing drought tolerance and optimizing yield performance. Zinc priming, whether applied alone or in combination with foliar treatments, has been shown to significantly improve energy dissipation in wheat, especially under drought stress (Pavia et al., 2019). Late-season foliar application of zinc has also proven beneficial, enhancing key agronomic traits such as photosynthesis, pollen viability, spike fertility, grain number per spike, water-use efficiency, and grain zinc concentration (Karim et al., 2012).

In agronomic terms, soil-based zinc fertilization has demonstrated substantial benefits, enhancing grain yield and zinc concentration across different drought severity levels. Increases in yield and grain zinc concentration ranging from 10.5% to 32.8% under

varying water availability status, with maximum benefits observed under drought conditions (Ma et al., 2017). This highlights the potential of soil-based zinc fertilization as a strategic tool for improving wheat crop resilience and productivity in drought-prone regions. In general, it could be inferred that optimizing zinc fertilization strategies, adjusted to specific environmental conditions and crop requirements, holds promise for enhancing the adaptive capacity of durum wheat crops to climate-induced stresses. Through augmenting nutrient availability and physiological resilience, zinc fertilization not only enhances crop yield and grain quality but also contributes to sustainable agricultural practices in the face of changing climatic conditions.

2.3.5. Sulphur's Effect on qualitative and quantitative traits

In addition to its direct effects on crop growth and grain yield, sulphur (S) deficiency in soil can significantly impact wheat quality, particularly through alterations in sulphur-containing proteins. Sulphur plays a vital role in the synthesis of prolamins, such as both sulphur-rich proteins, such as α - and γ -gliadins, and low-molecular-weight glutenin subunits (LMW-GS), as well as sulphur-poor proteins, like high-molecular-weight glutenin subunits (HMW-GS) and ω -gliadins (Wollmer et al., 2018). These proteins are vital components of the gluten matrix, with gliadins and glutenins being particularly important for the dough elasticity and strength required in bread making (Hussain et al., 2022). Any deficiency in sulphur availability not only affects yield but also compromises the overall quality of wheat by disrupting the protein composition essential for baking performance (Hussain et al., 2022). This highlights the need for balanced nutrient management strategies to ensure optimal grain quality in addition to productivity.

2.3.6. Nutrient Dynamics and Interactions: Implications for Crop Nutrition

The efficiency of nitrogen fertilization can potentially be enhanced by the addition of sulphur, highlighting that these two nutrients exhibit a strong synergistic effect when applied together through mineral fertilizers (Tabak et al., 2020). This synergistic interaction not only improves nitrogen uptake and utilization but also leads to increased crop yields and enhanced nutrient efficiency, emphasizing the importance of co-application in agronomic practices (Klikocka et al., 2017). The enhanced nitrogen uptake and utilization resulting from the presence of adequate sulphur levels leads to more efficient use of applied nitrogen, thus reducing potential losses and increasing agricultural output. However, in recent years, sulphur deficiency has become a growing concern, as

documented by numerous authors (Feinberg et al., 2021; Antošovský et al., 2024). This deficiency, largely attributed to reduced atmospheric sulphur deposition and the widespread use of sulphur-free fertilizers, highlights the importance of incorporating sulphur into fertilization strategies to ensure optimal nitrogen use efficiency and crop yields (Antošovský et al., 2024).

The interaction between sulphur and nitrogen is crucial for amino acid and protein synthesis, significantly affecting the nutritional quality and technological properties of wheat grains (Salvagiotti et al., 2009). A sufficient supply of both sulphur and nitrogen is essential for optimizing wheat yield and protein content (Zörb et al., 2010). A significant increase in grain yield of approximately 13.3% resulting from the combined and sufficient application of nitrogen and sulphur has been reported previously (Klikocka, and Marks, 2018). Additionally, a combination of foliar nitrogen and sulphur applied at the flowering stage was found necessary to achieve optimal protein quantity and quality in durum wheat (Jones, and Olson-Rutz, 2020). This indicates that neither nitrogen nor sulphur alone was sufficient to reach these levels, highlighting the synergistic effect of combining these nutrients. However, the effectiveness of sulphur fertilization in improving nutrient uptake and crop productivity is closely tied to its application rate. While sulphur has minimal impact when applied with low nitrogen levels, it significantly enhances nitrogen uptake and overall crop performance when combined with higher nitrogen rates (Talukdar et al., 2022). This demonstrates a clear synergistic relationship between sulphur and nitrogen, where the presence of adequate sulphur amplifies the benefits of nitrogen, leading to improved crop growth and yield.

The co-fertilization of nitrogen and sulphur has been shown to significantly enhance nutrient acquisition and improve grain quality in wheat, leading to a positive nutrient balance in the soil (Rathore et al., 2024). This synergy improves the ability of wheat crop to take up, utilize, and remobilize nitrogen, which is especially beneficial during critical growth stages including grain filling (Klikocka, and Marks, 2018; Roa et al., 2024). As a result, the wheat plants are able to accumulate more protein in the grain, improving the wheat grain quality and yield (Zörb et al., 2010). The presence of sulphur enhances the efficiency of nitrogen use, facilitating the production of sulphur-containing amino acids such as cysteine, which is vital for the structure and function of proteins (Liu et al., 2020). Cysteine is a crucial end product of sulphur metabolism and plays an important role in

the formation of disulphide bonds, which are essential for protein aggregation. These disulphide bonds are a key factor in determining the viscoelastic properties of the dough matrix, as they provide the structural integrity needed for the dough's extensibility and elasticity (Yu et al., 2018). The presence of sufficient cysteine, therefore, directly impacts the technological properties of wheat flour, particularly in processes such as bread, pasta and macaroni making where dough elasticity and strength are critical.

The observed synergistic effect between nitrogen and sulphur could be primarily attributed to the complementary roles these nutrients play in plant metabolism. Nitrogen is a fundamental component of amino acids and proteins, while sulphur is critical for synthesizing sulphur-containing amino acids like cysteine and methionine. These amino acids are essential for protein synthesis, which directly influences plant growth, grain quality, and yield. Given the crucial role of sulphur in enhancing nitrogen use efficiency and improving grain quality, integrating sulphur into nitrogen fertilization strategies is vital for achieving optimal wheat production outcomes. This approach is particularly important in regions where sulphur deficiency in soils is prevalent, as it ensures that nitrogen applications are more effective and contribute to both higher yields and superior grain quality.

While the synergistic effects of sulphur and nitrogen are well-documented, further research is needed to optimize the timing, forms, and application rates of these nutrients to maximize their benefits. Additionally, exploring the interaction of sulphur and nitrogen with other micronutrients in wheat, such as zinc and copper, could provide insights into more holistic fertilization strategies that support overall plant health and productivity. Another important interaction was also observed between nitrogen and zinc-containing fertilization. Growth traits were significantly enhanced by the combined application of nitrogen and zinc compared to their sole applications. The levels of photosynthetic pigments increased the most with the combined nitrogen and zinc applications, which were positively associated with improvements in biomass, growth, yield, and overall wheat grain quality (Shehzadi et al., 2024). This synergistic effect suggests that co-applying nitrogen and zinc can effectively boost both the physiological and agronomic performance of wheat, leading to better crop outcomes.

2.4. Varietal Differences and their Influence on Grain Yield and Nutritional Composition

Grain protein fractions are quantitative traits that result from a complex interaction of genetic factors, agronomic practices, and environmental influences. Wheat grains contain two main protein fractions: gliadins and glutenins. Gliadins contribute to dough viscosity, while glutenins are responsible for its elasticity (Zörb et al., 2018). These protein fractions play a crucial role in determining the quality of wheat-based food products (Bradová et al., 2012). The bread-baking quality of wheat is strongly associated with the presence of specific allelic variants of high molecular weight glutenin subunits (Wieser et al., 2008). Differences in grain protein content and composition among wheat varieties are shaped by their ploidy levels, developmental stages, and environmental conditions, underscoring the wide diversity observed among various wheat types (Khoa et al., 2020).

The grain protein content in durum wheat is also influenced by the yield potential of its genetic material. Many durum wheat varieties exhibit an inverse relationship between yield potential and grain protein concentration (Gebrewahid et al., 2020). High yielder varieties often show lower grain protein percentage, while low yielder varieties tend to have higher protein values. This disparity can be attributed to the ability of low yielder varieties to more efficiently convert available soil nitrogen into grain protein (Melash et al., 2019). The inverse relationship may also arise from genetic linkage, where genes that promote grain protein content are associated with genes that negatively impact yield. Therefore, selecting durum wheat varieties requires a careful balance between yield potential and grain protein concentration to optimize both productivity and quality.

The relationship between genetic potential and the nutritional composition of grain has shown inconsistency in previous studies. While the commonly observed inverse relationship suggests that high-yielding varieties typically have lower grain protein content, some high yielder varieties have also been reported to exhibit higher grain protein, increased gluten proteins, and favourable ratios of high molecular weight to low molecular weight gluten subunits (Visioli et al., 2018). This indicates that high productivity in durum wheat can potentially be paired with desirable quality traits through targeted breeding strategies (Visioli et al., 2018). These conflicting findings may arise from differences in growing conditions, varietal responses, and genotype-by-environment interactions. The genetic variability influencing grain protein content becomes

particularly evident when comparing modern durum wheat varieties with older cultivars, underscoring the impact of genetic improvements over time (Subira et al., 2014).

2.5. Impact of Seasonal Climatic Variations on Grain Yield and Nutritional Composition

Shifting rainfall patterns can lead to both immediate crop failures and long-term declines in agricultural productivity, primarily due to their detrimental effects on crop morphometric traits and yield-related characteristics. Drought stress, in particular, significantly hampers grain yield, with its impact often exacerbated when combined with other climatic factors (Pradhan et al., 2012; Qaseem et al., 2019). The interaction of these factors can produce synergistic, antagonistic, or hypo-additive effects on yield and associated traits (Prasad et al., 2011). Heat and drought stress can alter the growth and development rates of wheat, with the crop potentially completing its developmental stages more rapidly under water-limited conditions than under optimal circumstances (Ghazi, 2012). However, this accelerated growth limits the period available for assimilate accumulation throughout the growing season (Erda et al., 2005; Wahid et al., 2007). The physiological impacts of these stresses include reduced photosynthetic activity, irregular respiration patterns, stomatal closure, and elevated leaf temperatures, all of which contribute to a decrease in biomass production potential (Qaseem et al., 2019). Understanding the effects of heat and drought stress on durum wheat growth and development is vital for developing strategies to mitigate these challenges and ensure sustainable production amid changing environmental conditions.

Increased grain protein content not only enhances the quality of end-use products but also improves the crop's resilience to stress. Proteins play a critical role in stabilizing cellular membranes, thereby supporting the plant's survival under stressful conditions (Jamshidi et al., 2020). They are essential for sustaining metabolic functions, promoting plant growth, and enhancing drought tolerance by facilitating enzymatic reactions, cellular signaling, and stress responses (Merewitz et al., 2011). However, despite extensive research, establishing a consistent relationship between drought stress and grain quality attributes, particularly protein content, in durum wheat remains a challenge (Flagella et al., 2010; Gebrewahid et al., 2021). This challenge arises from the diverse responses seen in different crop ecotypes and genotype-by-environment ($G \times E$) interactions, making it difficult to develop a universal model. Additionally, variations in experimental

methodologies and the influence of multiple interacting factors further complicate efforts to consolidate research findings into a unified explanatory framework.

The relationship between drought stress and grain protein content in durum wheat is shaped by the variety, specific pedoclimatic conditions, and the interaction of these factors (Melash and Abraham, 2022). These complex interactions, along with potential synergistic effects, make it challenging to predict and manage the impact of drought stress on grain protein content. In many cases, drought leads to a significant decrease in grain protein content, with the extent of the reduction influenced by the timing and severity of the drought (Flagella et al., 2010; Gebrewahid et al., 2021). Research suggests that drought conditions can suppress the expression of key storage proteins, such as gliadin and glutenin, including specific fractions like α -gliadin and γ -gliadin, especially when water shortages occur during critical growth stages (Yang et al., 2011; Begcy and Walia, 2015). The decrease in grain protein concentration under drought stress is primarily attributed to restricted nitrogen availability and assimilation, as nitrogen is an essential component of storage proteins in grain (Zia et al., 2021). This reduction in protein content can negatively impact dough strength and stability, which in turn affects crucial technological traits such as loaf volume and valorimetric values—factors that are essential for determining the end-use quality of durum wheat (Tsenov et al., 2015).

Drought stress has been found to decrease the accumulation of essential minerals such as iron, zinc, nitrogen, phosphorus, and total protein content in developing grains of various crops (Sehgal et al., 2018). In addition to its impact on mineral content, drought stress also negatively affects the phytochemical composition of crops, leading to reduced levels of secondary metabolites such as phenolics, flavonoids, alkaloids, and terpenoids. These compounds are critical for a plant's defense against environmental stress and provide significant health benefits when consumed as part of a plant-based diet (Bindu et al., 2021). The decline in these beneficial phytochemicals under drought conditions not only compromises the plant's growth and resilience to stress but also diminishes the nutritional and therapeutic properties of crops, which has important implications for crop management and human nutrition.

Water stress during critical developmental stages, particularly during flowering and grain filling, can severely impair wheat growth and productivity. Insufficient moisture during these phases disrupts grain development, leading to marked reductions in plant height,

tiller production, biomass accumulation, and grain weight, as well as slower grain filling rates (Nouri et al., 2011). Drought stress also hampers leaf expansion and photosynthetic efficiency, resulting in fewer leaves per plant, smaller leaf sizes, and shorter leaf lifespans (Shao et al., 2008). These effects arise primarily from the plant's adaptive mechanism to conserve water, which limits leaf growth to maintain internal water balance and minimize water loss (Nezhadahmadi et al., 2013). The impact of drought stress is complex and can vary widely depending on the duration and severity of the drought, the plant's health and nutritional status, varietal differences, and the specific developmental stages at which drought occurs. Environmental factors also play a significant role in shaping these responses (Sun et al., 2017; Yu et al., 2018). Understanding these dynamics is essential for devising effective strategies to reduce the negative effects of drought stress on wheat production.

While nitrogen is well-known for its role in crop growth, development, and nutritional content, the interactions between nitrogen application rates, nitrogen sources, drought stress, and the specific phenological stages of durum wheat remain an area of ongoing research. Investigating how drought stress and varying nitrogen doses affect traits such as resource use efficiency, physiological parameters, and related characteristics can offer valuable insights into the development of drought-resistant crop varieties (Teixeira et al., 2014). Understanding these interactions is essential for optimizing nitrogen management while enhancing drought tolerance in crops. Furthermore, exploring the combined effects of nitrogen deficiency and drought stress can provide a deeper understanding of the physiological, biochemical, and phytochemical responses of durum wheat to water scarcity. These findings could support breeding and agronomic strategies focused on developing more resilient crop varieties that can better withstand the challenges posed by changing climatic conditions.

2.6. Emerging Technologies in Precision Agriculture for Nutrient Management

As the global population continues to rise, the need to increase wheat grain yield becomes more urgent, particularly as biotic and abiotic stresses present significant challenges (Fischer et al., 2014; Khobra et al., 2019). To meet the growing demand, a 40% increase in wheat production is required over the next two decades (Iqbal et al., 2021). Achieving high grain yield is heavily dependent on enhanced biomass accumulation and efficient resource allocation (Weina et al., 2022; Leilei et al., 2019). Efficient assimilate

partitioning into the developing spike and grain is crucial for determining wheat grain yield, particularly under both optimal and marginal growing conditions (John et al., 2011). High biomass production is closely linked to the canopy's ability to intercept photosynthetically active radiation (PAR), which is reflected in the leaf area index (LAI), contributing to the generation of new biomass (Tripathi et al., 2018). In addition, LAI, along with chlorophyll content indicators, serves as an important proxy for evaluating vegetation productivity and stress levels (Ma et al., 2023; Sanglard et al., 2014).

While a higher leaf area index (LAI) is typically beneficial for crop growth, it can also negatively impact varietal performance, leading to an estimated 8% reduction in overall productivity and a 10% decrease in grain yield due to shading, which impairs photosynthetic efficiency (Srinivasan et al., 2017). This suggests that many modern crop varieties may develop excess foliage that hinders optimal grain production, indicating that a controlled reduction in leaf area could improve yield potential (Srinivasan et al., 2017). The influence of physio-morphological traits on yield, and the dependence of grain production on factors like chlorophyll content, NDVI, plant height, LAI, and tiller formation, has been extensively documented (Roy et al., 2021; Tshikunde et al., 2019; Melash et al., 2019). Although existing research emphasizes the importance of these traits in boosting wheat yield, further studies are required to clarify their underlying mechanisms and address environmental constraints. Integrating genetic improvements with optimized agronomic practices could thus enhance wheat productivity by stabilizing physio-morphological traits and ensuring consistent yield performance across varied growing conditions.

While previous efforts to boost wheat grain yield have largely focused on increasing yield alone, considerable evidence suggests that a more comprehensive understanding of physiological and morphological traits can uncover synergies between agronomy and breeding, as well as between biomass accumulation and partitioning traits (Reynolds et al., 2009; John et al., 2011). This approach is essential not only for optimizing yield but also for ensuring the sustainability of wheat production systems. Advanced sensing technologies, such as NDVI and SPAD, have become invaluable tools for evaluating plant nitrogen status. These technologies allow for precise monitoring of nutrient dynamics, thereby enhancing agricultural practices and supporting more informed decision-making in nitrogen management (Qi et al., 2020; Kizilgeci et al., 2021).

NDVI and SPAD sensors have proven to be valuable tools for detecting nitrogen deficiency in the early growth stages of crops. While both provide essential insights, SPAD measurements demonstrate a stronger correlation with the plant's nitrogen status, particularly in response to applied nitrogen rates (Edalat et al., 2019). This indicates that SPAD offers a more precise and sensitive assessment of nitrogen content, making it particularly useful for evaluating nitrogen fertilization efficiency. Furthermore, SPAD readings show that early nitrogen applications significantly increase chlorophyll content, which is critical for robust early growth. However, as crops progress to later developmental stages, the predictive reliability of NDVI diminishes, highlighting the need for adaptive nitrogen management strategies (Hnizil et al., 2024). These findings emphasize the value of integrating both NDVI and SPAD measurements to optimize nitrogen and seeding rate decisions, thereby improving yields, enhancing sustainability, and minimizing environmental impacts.

NDVI values have demonstrated strong correlations with wheat yield variability, emphasizing their potential in guiding fertilization strategies that match crop needs throughout the growing season (Aranguren et al., 2020). SPAD measurements complement this by estimating chlorophyll content, which serves as a key indicator of plant nitrogen levels and photosynthetic activity (Rodrigues et al., 2018). The integration of advanced technologies, such as multispectral remote sensing and machine learning, has further advanced precision agriculture, enabling accurate crop monitoring and optimized resource allocation. This approach enhances both productivity and sustainability in wheat production (Badagliacca et al., 2024). NDVI plays a particularly vital role in boosting grain yield, with studies showing strong correlations between NDVI values, grain yield, and plant height. Research indicates that each 0.1-unit increase in NDVI can lead to a yield gain of approximately 1.1 to 2.6 t/ha (Milan et al., 2018; Ewa and Dariusz, 2020). Additionally, leaf chlorophyll concentration accounts for 8.8 to 10.9% of the variation in grain yield (Roy et al., 2021). However, the influence of chlorophyll content is influenced by developmental plasticity; for instance, lower chlorophyll levels during the grain-filling stage can be advantageous as the plant reallocates resources toward grain development (Araus et al., 2002).

3. MATERIAL AND METHODS

3.1. Planting Materials

The study evaluates ten promising varieties from Austria, Slovakia, and Hungary, including both spring- and winter-sown types, selected for their yield potential, stress tolerance, and 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, excellent tillering, stability, agronomic responsiveness, superior grain quality
Duragold	Spring	Mid-late	High yield potential, excellent tillering, stability, agronomic responsiveness, superior grain quality
Tamadur	Spring	Mid	Favourable agronomic traits, exceptional grain quality, disease resistance
Colliodur	Spring	Mid	High yield capacity, impressive drought tolerance, suited for water-limited conditions
MV Pennedur	Winter	Early-mid	High yield potential, strong gluten structure retention, exceptional stability, superior pasta quality
MV Pelsodur	Winter	Early	High yield potential, outstanding pasta quality, stress tolerance, high yellow pigment content, excellent cold tolerance, prone to lodging under nutrient-rich or wet conditions
MV Vékadur	Winter	Early	High grain yield, superior pasta quality, resistance to rust fungi and ear fusarium, may tilt under certain seasonal conditions
MV Hundur	Winter	Mid	Withstands environmental influences, tolerates abiotic stress, suitable for less intensive management systems
GK Julidur	Winter	Medium	Strong winter hardiness, drought tolerance, resistance to leaf and yellow rust, adaptable across diverse environments
Betadur	Winter	Mid	Reliable morphology, strong tolerance to dryness during later growth stages, suited for semi-arid conditions

Source: (<https://www.agronaplo.hu/agrarhirek/20210810/heti-fokusz-a-fajtavlasztas-a-durumbuza-eseteben-letkerdes-25883>).

3.2. Description of Study area

The plant materials were evaluated during the winter and spring seasons at the Látókép research center, University of Debrecen, Hungary, situated at 47°33'42" N, 21°27'02" E, approximately 15 km from Debrecen (Csajbók et al., 2020). The site features 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 revealed AL-soluble phosphorus at 57 mg kg⁻¹, AL-soluble potassium at 199 mg kg⁻¹, and zinc at 0.94 mg kg⁻¹. The soil sulphur content was 0.1 mg kg⁻¹. The water management characteristics of the soil were found to be favourable. Soil samples were collected from a depth of 0–20 cm at multiple locations before nutrient application during the experimental season.

The climate data for 2021, 2022, and 2023 were compared with the 30-year average to evaluate the impact of rainfall and temperature variations on crop production. 2021 was characterized as a dry year, with rainfall significantly lower than the long-term average in several key months (Figure 4). 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.

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. These wetter conditions in 2023, particularly during critical months, supported a better growing environment, mitigating the drought stress experienced in the previous two years.

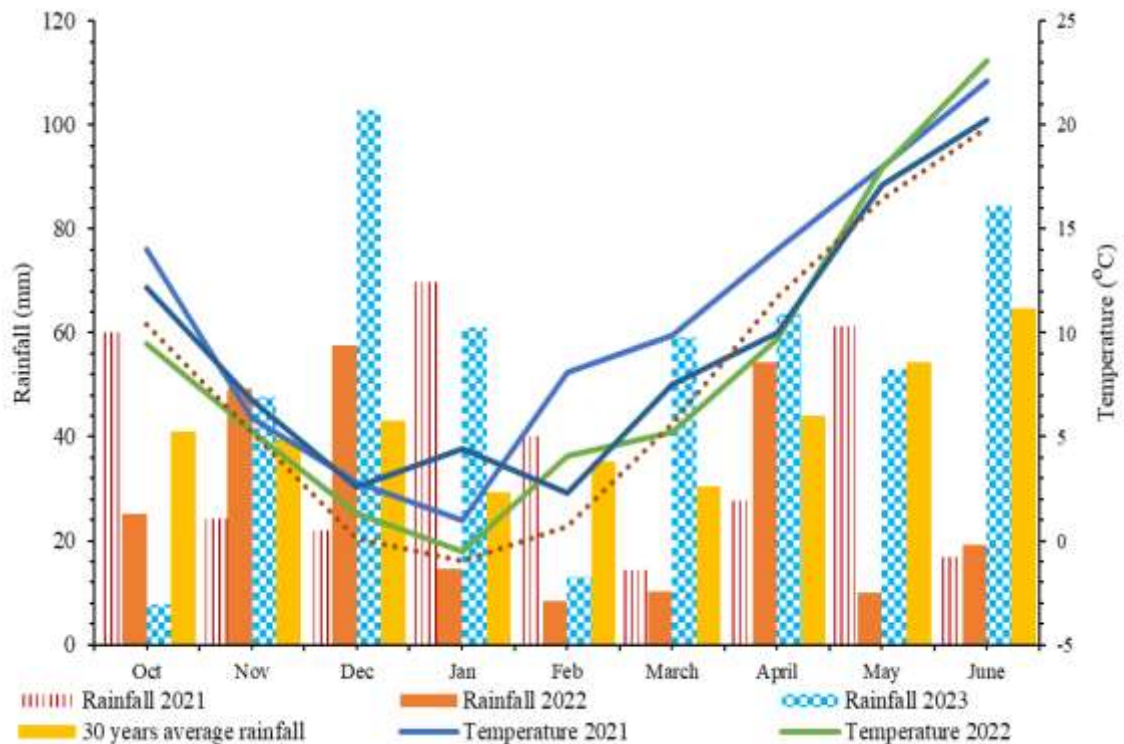


Figure 4. Illustrates the average monthly meteorological data—precipitation, and temperature—recorded at the Látókép experimental site throughout the 2021–2023 cropping seasons, providing a comparative analysis against meteorological data spanning 30 years.

Temperature trends were generally consistent with the rainfall patterns, although with notable deviations. 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.

3.3. Agrotechnical Conditions of the Field Experiment

Across three growing seasons (2021-2023), field agronomic practices were strategically organized around sequential tillage, targeted nitrogen fertilization, and integrated pest and disease control measures. Pest and disease management, utilizing herbicides, fungicides, and insecticides, was also implemented to minimize potential threats. Fungicide treatments, in particular, were applied at critical stages of the crop lifecycle to ensure disease control and support healthy crop development. Durum wheat cultivation over the three consecutive growing seasons (2020-2023) adhered to a well-structured agronomic approach. This included specific field operations designed to enhance soil fertility, optimize nutrient management, and maximize crop performance. Below is an overview of the field activities for each season, alongside the preceding crops that influenced subsequent nutrient treatments applied to the durum wheat crops.

First Growing Season (2020-2021): Field preparation for the first growing season began on September 17, 2020, with discing and rolling using a Güttler roller. A Carrier pass was then made on October 10, followed by a combinator pass on October 21 for seedbed refinement. Winter durum sowing occurred on October 23, while spring durum sowing was carried out on March 22, 2021. The first round of fertilization took place on March 25, followed by herbicide application (Granstar, 40 g ha⁻¹) on April 17. A second round of spring fertilization was applied on April 20, and fungicide treatment (Kantik, 2 l ha⁻¹) was administered on May 26. Insecticide application (Decis Mega) followed on June 4, and winter durum was harvested on July 13. Spring durum harvesting was completed on July 27.

Second Growing Season (2021-2022): The second season began with tillage operations on September 27, 2021, using disc and field cultivator passes, which were completed by October 2. Winter sowing occurred on October 19, and spring sowing was completed on March 18, 2022. A supplementary nitrogen fertilization treatment (40 kg ha⁻¹) was applied

on April 15, and fungicide treatment (Secator, 0.15 l ha⁻¹) was administered on April 21. Winter durum was harvested on July 5, and spring durum was harvested on July 15.

Third Growing Season (2022-2023): Field preparation for the third season began with basic tillage on September 24-25, 2022, using a disc and field cultivator, followed by seedbed preparation on October 10. Winter durum sowing took place on October 13, using a ring roller for soil consolidation. Spring fertilization began on March 13, 2023, with an application of 60 kg ha⁻¹, followed by seedbed preparation using a combinator. Spring sowing was conducted on March 14, with the first fungicide application (Riza, 1 l ha⁻¹) occurring on March 20. A second round of fertilization for the N2 plots (40 kg ha⁻¹) was applied on April 13, and a second fungicide treatment (Prozáró, 1 l ha⁻¹) was administered on April 27. Harvest for both winter and spring durum wheat took place on July 17.

Preceding Crops (2021-2023): The preceding crops were maize in 2021, sunflower in 2022, and sweet corn in 2023.

3.4. Experimental Design and Treatments

This study was conducted through a series of meticulously designed field experiments, spanning three consecutive years and covering both winter and spring seasons. The experiments aimed to evaluate various nutrient application strategies in a real-world agricultural context. Key variables included different fertilizer application rates, varietal differences, and foliar-applied nutrients, all compared against control groups. A comprehensive screening of ten durum wheat genotypes, representing varying adaptability to both winter and spring seasons, was conducted. The winter-adapted varieties included GK Julidur, GK Bétadur, MV Hundur, MV Pennedur, MV Vékadur, and MV Pelsodur, while the spring-adapted varieties included Colliodur, Durablank, Duragold, and Tamadur. These varieties were evaluated under specific winter and spring conditions to assess their performance across different seasonal environments.

The experimental treatments consisted of varying nitrogen application levels (control and 60 kg ha⁻¹ in 2021, and 60 kg and 100 kg ha⁻¹ in 2022 and 2023), ten durum wheat varieties, and three foliar-based fertilizer treatments (control, zinc, and sulphur). These treatments were arranged in a split-split plot design, with each treatment replicated three times to ensure statistical reliability and derive meaningful insights into the factors

influencing durum wheat responses. 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 m²), 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, thereby ensuring the accuracy and reliability of the experimental results. A liquid solution of sulphur and zinc, applied foliarly at the flag leaf stage, was used as fertilizers at rates of 4 liters ha⁻¹ for sulphur and 3 liters 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.

3.5. Data Collection Procedures and Measurements

The data collection was a careful process, involving a suite of sophisticated instrumentation and carefully devised sampling methodologies. 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. This section delineates procedures adopted, detailing the methodologies employed for data collection, the precision-driven measurements undertaken, and the systematic approach adhered to throughout the extensive period of research as the detailed describes as follow.

3.5.1. Physio-morphological traits

A Minolta SPAD-502 hand-held chlorophyll meter was used to assess the relative chlorophyll concentration and nitrogen status in durum wheat throughout both the spring and winter growing seasons. This non-destructive tool was employed from the early tillering stage to early maturity. The SPAD meter measures leaf transmittance at two specific wavelengths: 650 nm, which corresponds to the peak absorbance of chlorophyll, and 940 nm, which captures non-chlorophyll absorbance in the near-infrared range. This dual-wavelength approach allows for the determination of relative chlorophyll concentration, reflecting the plant's nitrogen status based on the principles outlined in Equation (1) (Markwell et al., 1995; Wood et al., 1993). Measurements were taken at

regular intervals during both growing seasons, providing continuous insights into the chlorophyll content and nitrogen status of the crop.

$$SPAD\ readings = A \times \left[\log \left(\frac{I_{or}}{I_r} \right) - \log \left(\frac{I_{of}}{I_f} \right) + B \right] \dots \dots \dots \text{Equation (1)}$$

Where:

A = constant;

B = constant;

I_{or} = current from red detectors with sample in place;

I_r = current from red infrared detectors with sample in place;

I_{of} = currents from red detectors with no sample;

I_f = currents from infrared detectors with no sample

A strict protocol was applied across all replications and experimental units to maintain consistency. For each test unit, the ten uppermost fully expanded and intact leaves were randomly selected for SPAD readings.

Leaf Area Index (LAI) measurements were carried out using the Delta-T SunScan SS1 COM-R4 portable plant canopy analyser system, which is equipped with a radio link (Delta-T Devices Ltd., UK). This system operates by measuring light transmission and analysing both incident and transmitted Photosynthetically Active Radiation (PAR) within the crop canopies. The portable system features a 100 cm long probe containing 64 PAR sensors, which cover a spectral range of 400 to 700 nm. The readings obtained from this system are expressed in units of PAR quantum flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$) and are then correlated with LAI units ($\text{m}^2 \text{m}^{-2}$). This method provides accurate and detailed measurements of the LAI, which is a crucial parameter for understanding canopy structure and assessing crop health and productivity.

The Normalized Difference Vegetation Index (NDVI) was measured at three to five distinct intervals throughout the life cycle of the durum wheat, providing a detailed assessment of crop health and vigour. The NDVI was calculated using Equation (2), which relies on the differential reflectance of near-infrared (NIR) and red light wavelengths—a method known for its sensitivity to vegetation health. To obtain the reflectance data, the sensor was passed over the center of each plot at a consistent height of approximately 50 cm above the crop canopy, covering a field of view of about 25 cm. Through conducting these measurements at specific intervals during critical growth stages, the NDVI offered insights into the physiological status and vigour of the durum

wheat, allowing for precise monitoring of the crop's development and potential stress factors.

$$NDVI = \frac{NIR - R}{NIR + R} \dots\dots\dots (2)$$

Where, **R** is the reflectance in the red range and **NIR** is the reflectance in the near-infrared range.

3.5.2. Harvesting and Grain Yield Determination

The grain yield was quantified using a Sampo Rosenlew SR 2010 plot combine harvester, featuring a Coleman weighing system. The harvesting was conducted within a designated 13.5-meter square area (1.5 × 9), ensuring a standardized and consistent sampling area across experimental plots. The plot combine harvester efficiently collected the grain, providing a direct measure of the yield in kilograms per hectare (kg ha⁻¹). This harvested grain was then standardized to a moisture content of 12.5% using established methodologies as outlined by Badu-Apraku et al. (2012). This adjustment is crucial to account for variations in moisture content, ensuring a uniform comparison of grain yields across different experimental units. This conversion enables a standardized comparison and analysis of grain yields, facilitating accurate assessments of durum wheat productivity across varying experimental treatments.

$$\text{Grain yield (kg ha}^{-1}\text{)} = \frac{100 - \% \text{ AMC}}{100 - \% \text{ SMC}} \times 100 \dots\dots\dots \text{Equation (3)}$$

Where;

AMC = Actual grain moisture content (%); SMC = Standard moisture content

3.5.3. Yield Associated Agronomic Metrics

Quantification of growth and yield attributes followed a systematic and standardized approach. For each biological replicate, five plants were selected from each technical replicate before harvesting. The measured attributes included spike length, number of tillers per square meter (SPD), number of seeds per spike (SPS), plant height, and awn length. Data from these five plants were averaged to represent one biological replicate. Spike length (SPL) was determined as the average length of five randomly selected spikes, measured from the base to the apex, excluding the awns. Plant height, spike length, and awn length were measured with a stainless steel scale, with measurements recorded

in centimeters. The number of seeds per spike (SPS) was measured by counting the seeds on each of the five randomly selected spikes. Spike density was assessed using 1×1 meter quadrants placed within the crop area. Within each square meter, a systematic count of the number of productive spikes was performed. This approach provided valuable insights into the crop's reproductive efficiency and potential yield by focusing on spike productivity within defined areas.

Lodging percentage (%): Lodging rates were calculated using the formula: (lodged area in the plot / total plot area) × 100%, at maturity across the replications (Chen et al., 2011).

3.5.4. 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.

3.5.5. Elemental Composition Analysis of the Grain

A chemical analysis was conducted to determine the elemental composition of 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.

To prepare the samples for analysis, the 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 (HNO₃, 69% v/v) (VWR International Ltd., Radnor, PA, USA) was added. The

mixture was left to react for 12 hours, after which the tubes were heated at 60°C for 30 minutes using a LABOR MIM OE-718/A block digestion apparatus. Once cooled slightly, 3 cm³ of hydrogen peroxide (H₂O₂, 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 minutes. Upon completion, the digested samples were allowed to cool before being diluted to a final volume of 50 cm³ 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 (Kovács et al., 1996) 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.

3.6. Statistical Data Analysis

The results are presented as mean values, with error bars representing the standard error (SE) of the mean difference. Statistical analyses were performed using GenStat (18th ed.) software (Payne et al., 2015). Prior to analysis, data normality was assessed using the Shapiro-Wilk test, with most parameters showing a normal distribution. Analysis of variance (ANOVA) was then conducted on the experimental data. If significant differences were detected by ANOVA, mean values for treatment groups were compared using the least significant difference (LSD) t-test ($p\text{-value} \leq 0.05$) to evaluate differences in nutrient expression levels under drought stress. Duncan's Multiple Range Test (DMRT) was applied for comparing interaction means, as shown in the graphs and tables.

Pearson's correlation coefficient was utilized to illustrate associations between pairs of measured traits. The strength of correlations in this study was categorized following the criteria outlined by Evans (1996). According to this classification, the absolute value of the correlation coefficient (r) is divided into five distinct groups: 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).

Principal Component Analysis (PCA), a multivariate statistical approach, was conducted using R-Studio to explore associations among multiple variables and reduce the dataset's complexity while retaining essential information. PCA was employed to identify patterns and correlations among key factors influencing durum wheat growth, including nitrogen levels, varietal differences, and seasonal variability, in relation to morphophysiological traits. This analytical approach provided valuable insights into the interactions between

these variables and their combined effects on durum wheat performance. The mean values derived from the analysis were used to generate visual representations, with graphs constructed using the graphing tools in Microsoft Excel to enhance data interpretation and facilitate a clearer understanding of the observed relationships.

4. RESULTS AND DISCUSSIONS

The analysis into the impact of nutrient management strategies on durum wheat grain quality, physio-morphological traits and yield stands as a pivotal investigation within the realm of the current doctoral research objective. The results and discussion section presents a synthesis of research results that elucidate the interactions between nutrient application strategies and their consequential effects on both the qualitative and quantitative dimensions of durum wheat production. Optimizing durum wheat productivity while ensuring sustainable agronomic practices presents an ongoing challenge, highlighting the importance of this study's results in clarifying the intricate relationship between nutrient management and the overall performance of the evaluated durum wheat varieties across diverse cropping seasons.

This study precisely evaluates a spectrum of parameters, including grain nutritional compositions, yield, and yield-associated metrics, to provide a holistic portrayal of the multifaceted ramifications stemming from distinct nutrient management approaches under naturally imposed wet and dry cropping seasons, aimed at deciphering their individual and collective impacts on the studied traits. Throughout the results and discussion section, a careful analysis of the empirical findings reveals observed trends, disparities, and correlations that emerge from the experimental data. This section includes a comprehensive investigation centered on three main themes, each addressing distinct facets of durum wheat productivity and sustainability.

The **first** theme focuses on yield and its components, exploring how different varieties of durum wheat respond to varying nitrogen levels and seasonal fluctuations. This analysis provides valuable insights into adaptive strategies and effective agricultural management practices. The **second** theme of the dissertation examines nutrient management strategies, varietal influences, and seasonal variability concerning key physiomorphological metrics such as LAI, NDVI, and SPAD values. This investigation highlights the dynamic interactions between agronomic practices and environmental conditions, which are crucial for optimizing crop health and productivity. The **third** theme addresses comprehensive nutrient management techniques aimed at enhancing productivity and improving nutritional compositions including zinc, and iron concentration, while also elevating quality attributes such as protein content in durum wheat.

4.1. Harnessing Durum Wheat Diversity and Nutrients Management to Optimize Grain Yield Under Divergent Cropping Season

4.1.1. 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 (Figure 5). 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, indicating their ability to effectively utilize additional nitrogen for increased productivity. 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.

The main effect of durum wheat varieties on grain yield was also significant ($p < 0.05$) in the 2021 cropping season. This indicates the critical role of genetic traits in determining yield performance under water-limited conditions. The spring-sown varieties produced lower yields, with Duragold (7000 kg ha⁻¹) and Durablank (6851 kg ha⁻¹) performing best in this group. However, Tamadur proved to be particularly drought-sensitive, exhibiting a considerable reduction in grain yield during the challenging growing season. These results emphasize the importance of genetic selection in mitigating the detrimental effects of drought on durum wheat productivity. The higher yields of winter-sown varieties further suggest their ability to utilize limited water resources more efficiently, likely due to their longer growing periods and well-developed root systems that enhance moisture uptake. Julidur, Betadur, and Pelsodur demonstrated exceptional resilience, making them promising candidates for cultivation in drought-prone regions.

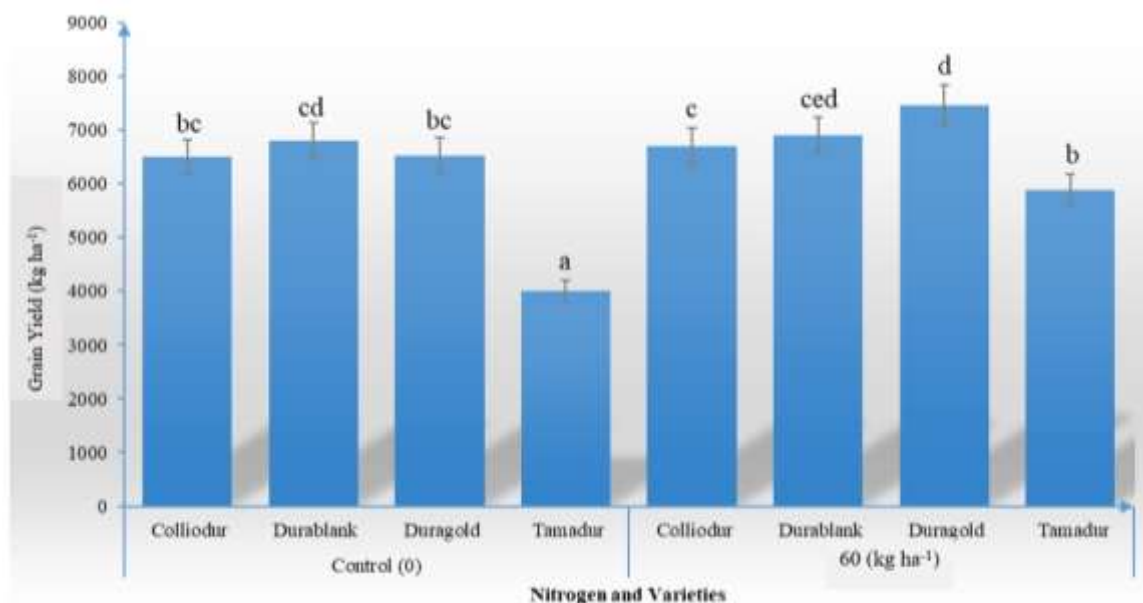


Figure 5. Yield performance of durum wheat varieties with and without nitrogen fertilization under drought conditions during the 2021 cropping season, Debrecen-Látókép.

The combined analysis of variance indicated a statistically significant three-way interaction between durum wheat varieties, foliar applications of zinc and sulfur, and nitrogen application rates concerning grain yield (Figure 6). In the absence of nitrogen application, no significant differences in grain yield were observed among the tested durum wheat varieties—Colliodur, Durablank, and Duragold—despite foliar nutrient applications. This suggests that these varieties did not exhibit a significant sensitivity to nutrient supplementation under nitrogen-limited conditions. However, a notable exception was observed with the variety Tamadur, which showed a significant improvement (5.24%) in yield when treated with sulfur containing fertilizers, indicating the differential nutrient responses among durum wheat varieties.

Although nitrogen was not applied, the foliar application of sulfur-based fertilizers alone resulted in a significant ($p < 0.05$) increase in grain yield by 22.807% for Tamadur, achieving a yield of 4690 kg ha⁻¹ (Figure 6). This outcome suggests that sulfur, a secondary macronutrient, could play a key role in mitigating the negative impacts of drought on durum wheat productivity by enhancing nutrient utilization and promoting stress tolerance. When 60 kg ha⁻¹ of nitrogen was combined with sulfur, the yield increased further to 6088 kg ha⁻¹, demonstrating a synergistic effect between nitrogen and sulfur. This enhanced response indicates that nitrogen can improve the crop's ability to efficiently use sulfur, optimizing plant growth under water-limited conditions. The

interaction between sulfur and nitrogen may be linked to improved nutrient uptake, better physiological functioning, and increased NUE, which are crucial for maintaining crop productivity under drought stress.

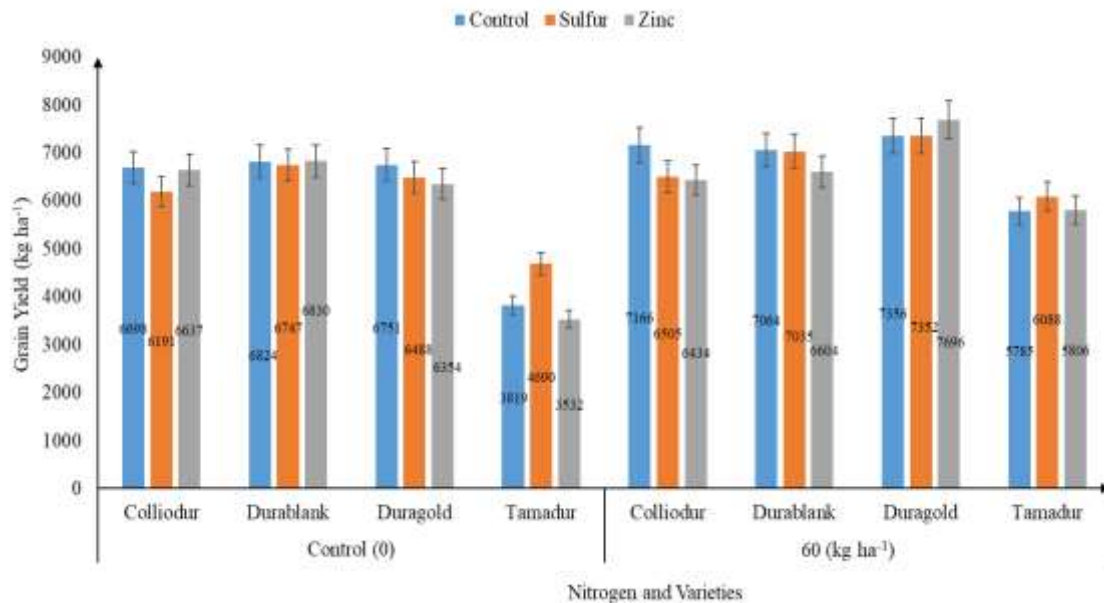


Figure 6. Interaction effects of nitrogen, durum wheat varieties, and foliar zinc and sulphur application on grain yield during the 2021 cropping season, Debrecen-Látókép.

The combination of nitrogen and sulfur appears to have a more substantial impact on yield than either nutrient applied alone, suggesting that integrated nutrient management—incorporating both macronutrients and micronutrients—can serve as an effective strategy for mitigating drought stress. This approach is particularly relevant in regions prone to water scarcity, where optimizing nutrient management could enhance the durum wheat’s ability to tolerate water stress and improve yield stability. The synergistic effects observed in this study call for further research into the interactions between nitrogen and sulfur, as their combined application holds promise for developing drought-resilient strategies that ensure food security in arid and semi-arid regions. This approach is especially relevant in regions where nitrogen is applied in suboptimal quantities, and sulfur may be used to enhance the crop’s nutritional and physiological status. The synergistic effects observed in this study advocate for more research into the interactions between nitrogen and sulfur, as well as the broader implications of their combined application in sustainable agricultural practices.

Interaction effects between nitrogen, sulfur, and zinc were particularly pronounced in the varying varietal responses. Duragold demonstrated the most significant benefit from the combined nitrogen and zinc applications, achieving a 5.29% yield increase compared to the nitrogen-only control. In contrast, Colliodur and Durablank showed either marginal or negative responses to sulfur and zinc applications, suggesting potential nutrient imbalances or varietal differences in nutrient uptake and utilization efficiency. Tamadur's low baseline yield under unfertilized conditions and its substantial response to nitrogen and sulfur applications emphasize its dependency on adequate nutrient inputs for improved productivity. These results are consistent with previous research, which indicates that nutrient interactions significantly influence crop performance under varying environmental and management conditions (Melash et al., 2023). The yield reductions associated with sulfur applications in certain varieties may be attributed to nutrient antagonism with nitrogen, while Duragold's positive response to zinc highlights its enhanced nitrogen assimilation and utilization efficiency.

4.1.2. Seasonal Adaptation of Durum Wheat to Differential Nitrogen Inputs

Building on the observation that nitrogen fertilization, in combination with foliar-applied nutrients, played a pivotal role in mitigating drought effects and enhancing grain yield 2021 cropping season, further studies were conducted during the 2022 and 2023 cropping seasons. These studies aimed to investigate the impact of doubling the nitrogen rate, alongside the foliar application of zinc and sulphur, on the nutrient responsiveness of durum wheat varieties (both winter and spring-sown). The varieties were treated with nitrogen application rates of 60 kg ha⁻¹ and 100 kg ha⁻¹ to evaluate their performance under varying seasonal conditions and to explore the differential responses between the two sowing types.

The current study unequivocally demonstrates that genetic variability among durum wheat varieties significantly ($p < 0.001$) impacts grain yield in response to different nitrogen fertilization rates. The highest (7500.72 kg ha⁻¹) grain yield was achieved by the variety MV Pelsodur under the lowest nitrogen rate (60 kg ha⁻¹), followed by MV Hundur (6510.22 kg ha⁻¹), indicating exceptional efficiency in utilizing lower nitrogen levels (Table 2). While nitrogen fertilization played a crucial role in overall yield, the inherent genetic potential of MV Pelsodur, as manifested in its longer spikes, may have provided a foundation for greater grain number and ultimately higher yield (Table 2). In contrast,

variety Tamadur attained a significantly lower grain yield (4248 kg ha⁻¹) under the lowest nitrogen rate but showed improvement (5542.78 kg ha⁻¹) at higher nitrogen rates (100 kg ha⁻¹), suggesting a higher nitrogen requirement for optimal productivity (Table 2). The 43.4% difference in grain yield between the high-yielding varieties (MV Pelsodur) and the low-yielding variety (Tamadur) at the lowest nitrogen rate highlights the genetic predisposition of certain varieties, such as MV Pelsodur and MV Hundur, for higher productivity and adaptability to nitrogen fertilization. In the contrary, Tamadur's lower grain yield under suboptimal nitrogen conditions suggests potential limitations in its genetic traits or responsiveness to nitrogen fertilization, resulting in reduced productivity.

Table 2. The interaction effect analysis between durum wheat varieties and nitrogen levels concerning yield, and associated yield metrics.

N rate (kg ha ⁻¹)	Growth habit	Varieties	PH (cm)	SPL (cm)	SPD (m ²)	GPC (%)	LDG (%)	GY (kg ha ⁻¹)
60	Winter	GK Bétadur	75.96	6.81	525.30	15.33	44.72	5704.13
		GK Julidur	73.51	5.84	506.40	15.12	42.78	6349.78
		MV Hundur	86.76	6.76	499.30	14.90	44.72	6510.22
		MV Pelsodur	83.59	7.47	460.00	14.46	28.89	7500.72
		MV Pennedur	84.89	5.98	507.30	15.11	44.67	6386.09
		MV Vékadur	87.07	7.07	511.60	14.43	43.06	6456.74
	Spring	Durablank	69.09	4.46	341.60	15.80	-----	4592.09
		Duragold	69.16	4.65	348.00	15.09	-----	5090.03
		Tamadur	69.04	4.53	371.30	14.57	-----	4248.03
100	Winter	GK Bétadur	78.58	6.36	484.90	15.84	52.78	4667.12
		GK Julidur	74.62	5.78	526.90	16.54	50.00	5570.78
		MV Hundur	88.11	6.78	501.60	15.82	55.00	6098.42
		MV Pelsodur	86.40	7.72	479.60	14.18	31.39	7438.99
		MV Pennedur	86.51	6.24	518.70	15.02	47.78	6447.23
		MV Vékadur	86.56	7.12	550.90	15.71	50.56	6402.80
	Spring	Durablank	70.67	6.47	369.80	15.36	-----	5011.71
		Duragold	71.51	6.28	382.40	15.67	-----	5529.38
		Tamadur	70.76	6.56	391.30	15.03	-----	5542.78
LSD _{0.05}			5.60	0.69	32.97	1.02	3.75	395.77
CV (%)			4.5	6.9	3.1	3.50	8.80	2.90

Key to abbreviations: N; Nitrogen, PH (cm); Plant height, SPL (cm); Spike length, SPD (m²) Spike density, GPC (%); Grain protein content, LDG (%); Lodging, GY (kg ha⁻¹); Grain yield, LSD_{0.05}; Least significant difference, CV (%); Coefficient of variation

The pronounced genotype-by-nitrogen (G×N) interaction in durum wheat production highlights the critical role of genetic variability in determining the response to nitrogen fertilization. G × N interactions indicate that each variety's performance across varying nitrogen conditions is inherently linked to its genetic makeup. This suggests that a variety

excelling under high nitrogen conditions may not necessarily thrive under low nitrogen levels, a concept supported by differential genetic value correlations across nitrogen environments (Cormier et al., 2016). This result has significant implications for agronomic practices, suggesting that optimizing nitrogen management requires careful consideration of varieties selection. The superior performance of MV Pelsodur and MV Hundur under low nitrogen conditions is particularly noteworthy, as it implies potential cost savings for farmers without compromising yield. In contrary, the strong yield responsiveness of the variety Tamadur to increased nitrogen application highlights the importance of precise nitrogen management.

While Tamadur's significant yield increase under higher nitrogen rates suggests its potential for high productivity, there might be notable environmental risks associated with excessive nitrogen use. The over-application of nitrogen not only reduces NUE but also contributes to serious environmental consequences, such as nitrate leaching into water bodies and the emission of nitrous oxide (N₂O), a potent greenhouse gas that plays a significant role in climate change (Wang et al., 2023). These environmental concerns underline the importance of carefully balancing nitrogen inputs to avoid surpassing the nitrogen saturation threshold, where additional nitrogen no longer translates to yield gains but instead results in negative externalities. While most varieties demonstrated varying degrees of nitrogen responsiveness, MV Pelsodur emerged as a standout performer, consistently delivering high grain yields across both low and high nitrogen treatments. At 60 kg ha⁻¹ of nitrogen, MV Pelsodur achieved a grain yield of 7500.72 kg ha⁻¹, while at 100 kg ha⁻¹ of nitrogen, it reached 7438.99 kg ha⁻¹ (Table 2). This stability in yield, coupled with minimal response to increased nitrogen input, indicates exceptional nitrogen-use efficiency.

Varieties that demonstrate lower yield reductions under high nitrogen conditions are likely more tolerant to excess nitrogen, which could be due to more efficient nitrogen uptake and utilization mechanisms or better adaptability to the associated environmental stresses (Aga et al., 2022). The variety's consistent performance, irrespective of nitrogen availability, positions it as a valuable resource for regions where nitrogen inputs are constrained or where minimizing nitrogen use is a priority for environmental sustainability. Reducing nitrogen application effectively alleviated yield reduction and enhanced water and nitrogen use efficiency in winter wheat subjected to post-anthesis combined stress (Ru et al., 2024). Hence, incorporating germplasm from MV Pelsodur

into breeding programs could lead to the development of varieties that are more resilient to nitrogen fluctuations, ultimately enhancing grain yield stability and reducing environmental impacts. This capability to adapt to diverse nitrogen conditions could improve grain yield stability and contribute to more sustainable agronomic practices by optimizing nitrogen use efficiency (Aga et al., 2022).

The contrasting performance of MV Pelsodur and Tamadur under varying nitrogen conditions demonstrates the value of developing flexible, variety-specific nitrogen management strategies. In varieties like Tamadur, where higher nitrogen inputs drive yield gains, nitrogen applications should be calibrated to maximize productivity without exceeding environmental thresholds. In contrast, for varieties such as MV Pelsodur that maintain stable yields under low nitrogen conditions, lower nitrogen input strategies could be employed, making them ideal for regions with nitrogen-limited resources or for systems focusing on sustainability. The insights from this study reinforce the broader agronomic principle that optimizing nitrogen management requires an integrated approach that accounts for both genetic and environmental factors. As the agricultural sector faces increasing pressure to reduce its environmental footprint, breeding programs and agronomic practices must converge to promote the development of wheat varieties with improved NUE and to establish nitrogen application strategies that maximize yield while minimizing ecological impact.

The effectiveness of nitrogen application in improving grain yield was significantly ($p < 0.001$) influenced by the interaction between cropping calendar (i.e., winter and spring) and crop genetic differences. Increasing the nitrogen application rate from 60 kg ha^{-1} to 100 kg ha^{-1} resulted in enhanced grain yield for spring-sown durum wheat varieties, with significant improvements observed particularly for varieties such as Durablank (9.10%) and Tamadur (30.48%) (Table 2). This suggests that spring-sown varieties may have a higher capacity to utilize additional nitrogen inputs effectively, translating into significant yield gains. These improvements could be attributed to the physiological and morphological traits of these varieties, which enable more efficient nitrogen uptake and utilization during the cooler growth conditions typically experienced during spring planting. However, the opposite effect was observed for some winter-sown varieties, where increasing nitrogen application up to 100 kg ha^{-1} led to a reduction in grain yield.

Varieties such as GK Julidur experienced a 12.27% decrease in grain yield, while GK Bétadur showed an even more substantial reduction of 18.18% under high nitrogen application rates (Table 2). A decrease in grain yield has been previously reported due to high nitrogen application rates, with the extent of this effect varying according to the genetic makeup of the varieties (de Lima et al., 2021; Chen et al., 2023). The observed plateau effect is universally a critical consideration in optimizing nitrogen use, as excessive nitrogen application beyond this point could lead to diminishing returns or even negative environmental impacts, such as nitrate leaching or greenhouse gas emissions. The effectiveness of nitrogen application in enhancing grain yield is influenced not just by the genetic variation among wheat varieties but also by agronomic practices and environmental factors.

The negative impact of nitrogen application rates on grain yield in winter durum wheat varieties could arise from differences in growth patterns, nutrient uptake dynamics, environmental conditions, physiological traits. While winter-sown varieties generally produced higher grain yields than their spring counterparts, their response to increased nitrogen levels was notably less pronounced (Table 2). A significant reduction in grain yield observed under high nitrogen conditions in winter-sown varieties suggests that these varieties may have a lower nitrogen saturation threshold compared to spring-sown varieties. This reduced responsiveness implies that winter-sown varieties may have reached a nitrogen saturation point, where further nitrogen applications do not translate into yield gains and instead may have adverse effects. These effects could include excessive vegetative growth, nutrient imbalances, and increased susceptibility to lodging, all of which can detract from overall yield potential (Qaswar et al., 2024).

The notion of a nitrogen saturation point is consistent with the law of diminishing returns, where the benefits of additional nitrogen decrease as the application rate exceeds the plant's optimal requirement (Klikocka, and Marks, 2018). These emphasize the importance of balanced nitrogen application in wheat cropping systems (Tian et al., 2023). Additionally, winter wheat starts nutrient absorption during late fall and winter without significant growth, in contrast to spring wheat, which begins nutrient uptake in spring as it grows (Weih et al., 2016). Although winter wheat may absorb nutrients at increased rates early in the growing season, this does not lead to a proportional increase in growth, indicating a lag in growth response relative to nutrient uptake (Weih et al.,

2021). This suggests that winter wheat can effectively utilize nutrients prior to significant vegetative growth, potentially influencing its overall growth and yield potential.

Winter-sown durum wheat varieties generally benefit from a longer growing period, which can inadvertently increase the risk of nitrogen leaching or volatilization, particularly when excessive nitrogen is applied (Abubakar et al., 2023). These processes can lead to significant nitrogen losses from the soil, reducing the availability of nitrogen during the critical grain-filling stage and ultimately impacting yield negatively. When nitrogen levels exceed optimal thresholds, they may also disrupt the plant's nutrient balance, hindering the uptake of other essential nutrients such as potassium and phosphorus (Li et al., 2019). In contrast, spring-sown varieties, which develop under warmer temperatures and longer daylight conditions, may possess a greater capacity to assimilate higher nitrogen levels, leading to increased grain yield. These differences further suggest the necessity of integrating both growing environment and varietal characteristics into nitrogen management strategies.

The main inference drawn is that the contrasting responses observed among the tested durum wheat varieties highlight the necessity for adjusted nitrogen management practices. This adaptation would allow nitrogen application to be more closely aligned with each variety's specific growth requirements and environmental interactions, thereby optimizing yield and resource use efficiency. Winter-sown varieties are likely to benefit from more conservative nitrogen applications. Lower application rates (60 kg ha^{-1}) can help avoid exceeding their nitrogen threshold, which could trigger yield-limiting effects. In contrast, spring-sown varieties generally exhibit a clear yield advantage with higher nitrogen application (100 kg ha^{-1}) rates, justifying a more liberal approach to nitrogen use for these varieties. Over-application not only risks failing to improve yields but can also contribute to environmental degradation, manifesting through issues such as nitrogen leaching and increased greenhouse gas emissions (Zhao et al., 2019). In both scenarios, it is crucial to optimize nitrogen management to mitigate the risks associated with over-application. This approach highlights the importance of combining genetic, agronomic, and environmental factors into well-rounded nitrogen management strategies, ensuring applications are balanced—neither excessive nor inadequate. Such an integrated approach can enhance nitrogen use efficiency, promoting sustainable yield improvements while reducing potential environmental impacts (Sandhu et al., 2021).

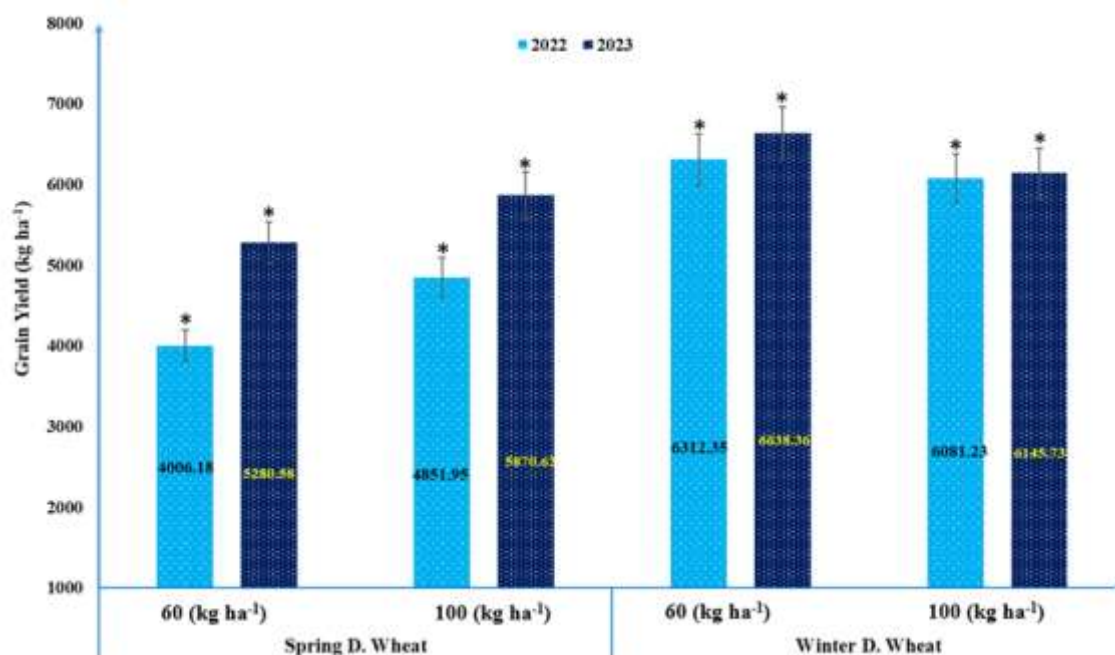


Figure 7. The seasonal and crop species variations in nitrogen requirements and corresponding nitrogen application rates, average over the tested varieties, Debrecen-Látókép, 2022-2023. Bars indicated with single asterisks are statistically significant at 0.05%.

Although genetic variation among durum wheat varieties does influence their response to nitrogen fertilization rate, the impact of cropping season often overshadows these genetic differences. This is evident from the significant interaction ($p < 0.001$) between nitrogen application rates, genetic variation, and cropping season dynamics, which collectively shape nitrogen requirements and subsequent grain yield, with effects differing notably between spring-type and winter-type varieties (Table 3; Figure 7). Applying nitrogen at a rate of 100 kg ha^{-1} enhanced grain yield in spring-sown durum wheat (sown in late winter or early spring) varieties across different cropping seasons and moisture conditions. In years with adequate moisture, such as 2023, this higher nitrogen rate led to an 11.17% yield increase, demonstrating the variety's ability to effectively utilize nitrogen under favourable conditions. In dry seasons (2022), the effectiveness of this application rate is even more pronounced, improving yield by up to 21.11% (Figure 7). Similar findings have been reported in previous studies, which indicated that under dry climatic conditions, a higher nitrogen rate effectively enhances grain yield in spring wheat, while further increases yield diminishing returns (Wang et al., 2023).

Table 3. Grain yield response to variations in growing season and nitrogen fertilizer rate

Varieties	60 (kg ha ⁻¹)	100 (kg ha ⁻¹)
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Growth Habit	2022		2023		
	2022	2023	2022	2023	
Winter	GK Bétadur	5902 ^{fg}	5507 ^{ef}	4215 ^b	5119 ^{de}
	GK Julidur	6406 ^{ijklm}	6294 ^{hijkl}	5590 ^{efg}	5552 ^{ef}
	MV Hundur	6160 ^{hijk}	6860 ^{mn}	6160 ^{hijk}	5916 ^{fg}
	MV Pelsodur	6412 ^{ijklm}	8589 ^p	6794 ^{lmn}	8083 ^o
	MV Pennedur	6369 ^{ijklm}	6403 ^{ijklm}	6502 ^{ijklm}	6392 ^{ijklm}
	MV Vékadur	6625 ^{klm}	6288 ^{hijk}	7216 ⁿ	5589 ^{efg}
Spring	Durablank	4426 ^{bc}	4758 ^{cd}	4820 ^{cd}	5203 ^{de}
	Duragold	4338 ^{bc}	5842 ^{fgh}	4974 ^d	6085 ^{ghij}
	Tamadur	3255 ^a	5241 ^{de}	4762 ^{cd}	6324 ^{hijkl}
LSD _{0.05}	503	503	503	503	
CV (%)	5.80	5.80	5.8	5.8	

In contrast, the effects of nitrogen application at a rate of 100 kg ha⁻¹ on winter-type durum wheat varieties (sown in autumn or early winter) reveal significant variability depending on the moisture levels during the growing season. In seasons with sufficient moisture, such as the 2023 cropping year, the application of 100 kg ha⁻¹ of nitrogen resulted in a notable reduction in productivity of winter sown varieties by 7.42% (Figure 7). This decrease in grain yield highlights the sensitivity of winter-type durum wheat to excessive nitrogen under adequate moisture conditions, potentially due to imbalanced plant growth, reduced root development, and increased susceptibility to lodging. However, during dry cropping (2022) years, the negative impact is somewhat mitigated but still results in a 3.66% decrease in grain yield, emphasising the variability in response to nitrogen application among different durum wheat types (Figure 7). This adverse effect is likely attributed to nitrogen excess, which can lead to imbalanced plant growth, reduced root development, increased susceptibility to lodging, and inefficient nutrient utilization.

Yield fluctuations in both winter and spring wheat varieties are influenced by climatic and agronomic factors, with seasonal climate variability explaining approximately one-fifth of the observed yield variation (Han et al., 2023). This result suggests that while nitrogen management plays a crucial role in optimizing yield, understanding the broader climatic context is essential for effective crop production strategies. Furthermore, spring-sown varieties demonstrate a higher nitrogen demand and can efficiently utilize additional nitrogen, even under sufficient moisture conditions.

The seminal previous results highlight the pivotal role of moisture availability during the growing season in shaping total crop N demands (Zhang et al., 2017). In dry cropping

systems, crops may struggle to acquire banded nitrogen fertilizer, leaving it stranded in the topsoil and vulnerable to losses, ultimately impacting grain yield (Rowlings et al., 2022). The interaction between water and nitrogen significantly influences plant growth and yield; optimal water conditions enhance root development and nitrogen uptake efficiency, while both insufficient and excessive water can hinder nitrogen utilization, reduce crop yields, and lead to environmental issues such as soil nitrogen loss and groundwater pollution (Ma et al., 2023). This observation universally highlights that the interaction between nitrogen application rates and moisture availability significantly influences the productivity of winter-type durum wheat varieties, emphasizing the necessity for adjusted nutrient management strategies that account for environmental conditions to optimize yield outcomes and mitigate the adverse effects of excessive nitrogen fertilization.

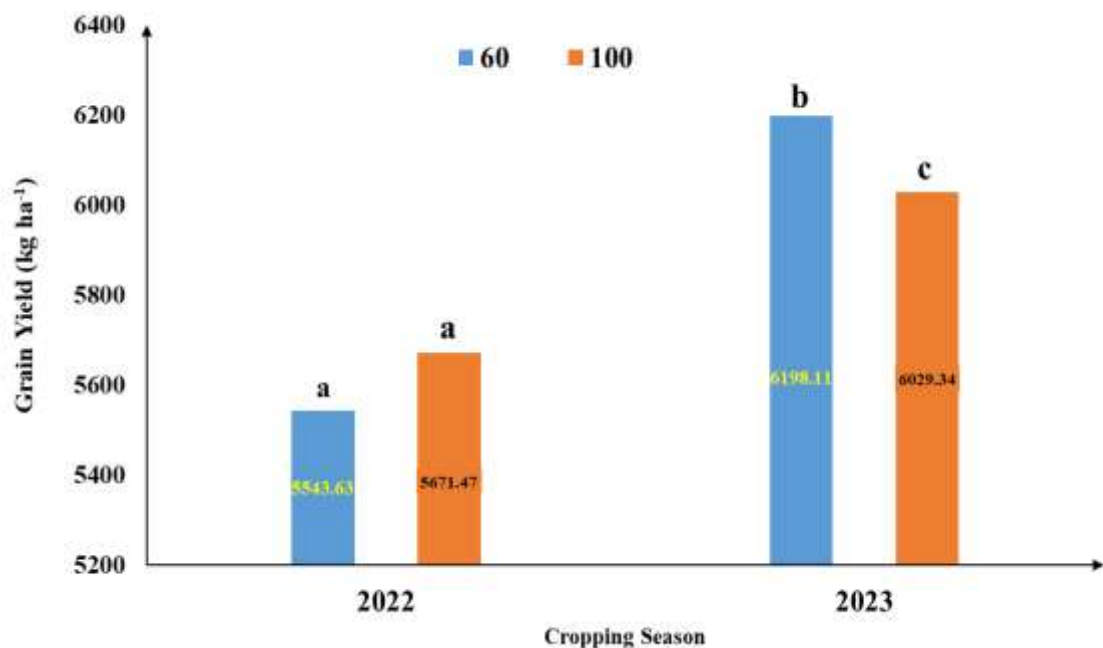


Figure 8. Impact of seasonal variation on nitrogen application rate and its effect on yield, Debrecen-Látókép, 2022-2023 cropping season. Bars labelled with the same letter indicate no statistical difference, while bars with different letters are statistically significant at 0.05%.

Although interactions between nitrogen application rates and cropping years resulted in some reduction in grain yield, the overall impact of these interactions was less pronounced compared to the combined effects of durum wheat varieties, growing seasons, and nitrogen rates (Table 2; Table 3). Nitrogen application significantly influences durum wheat grain yield, with effects ranging from optimal yield at 60 kg ha⁻¹

¹ to potential declines at 100 kg ha⁻¹, regardless of the growing season. In the wet 2023 cropping year, grain yields were generally higher compared to the drier (2022) cropping season (Figure 8). However, doubling the nitrogen application rate resulted in a 2.52% decrease in grain yield in 2023 but a 2.31% increase in yield during the 2022 cropping season (Figure 8). This variability hinges on the specific characteristics and pedoclimatic conditions of the growing season, and highlights the role of seasonal climate variability in shaping the outcomes of nitrogen management in durum wheat production. These results suggest that in water-limited cropping seasons, achieving maximum grain yield may require a higher nitrogen application rate compared to wetter years. Adjusting nitrogen management practices in alignment with specific growing location, varietal difference and growing season will optimize wheat productivity and sustainability has been also previously reported (Magyar, 2021).

The general trend of achieving maximum grain yield at lower nitrogen levels is evident, but specific outcomes are highly dependent on the interaction between environmental factors and genetic traits. In relatively dry seasons, additional nitrogen may alleviate nutrient limitations, promoting crop growth and increasing grain yield (Szilvia et al., 2018). However, the reduction in grain yield observed during wet cropping years can be attributed to the adverse effects of excessive nitrogen application, such as exacerbating lodging, nutrient leaching, and other negative impacts, despite favourable moisture conditions (Noor et al., 2023). The contrasting response to nitrogen application between wet and dry cropping seasons indicating the complex interaction between nitrogen availability and environmental conditions. As a result, optimal nitrogen levels should not be considered static but rather adjusted based on prevailing moisture conditions and the specific needs of each growing season. These practices ultimately enhance the sustainability and ensure the profitability of durum wheat production.

4.1.3. Improving Durum Wheat Yield Potential Through Strategic Foliar Zinc and Sulphur Applications

In the 2021 cropping season, which was characterized as a dry season, the exogenous application of sulphur likely contributed to better osmotic regulation, improved enzymatic activity, and enhanced nitrogen metabolism, leading to a significant ($p < 0.05$) increase in grain yield, particularly in spring-sown durum wheat varieties (Figure 9). 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 4802 to 5389 kg ha⁻¹ compared to the control group (Figure 9). This substantial yield improvement highlights the critical role of sulphur in supporting grain yield under drought conditions. These notable differences are likely attributed to the uptake efficiency of the wheat varieties and the interaction between applied inputs and other metal ions at various physiological levels. It is important to highlight that limited sulphur availability may result in reduced growth and grain yield, especially in resource-constrained environments (Usmani et al., 2020).

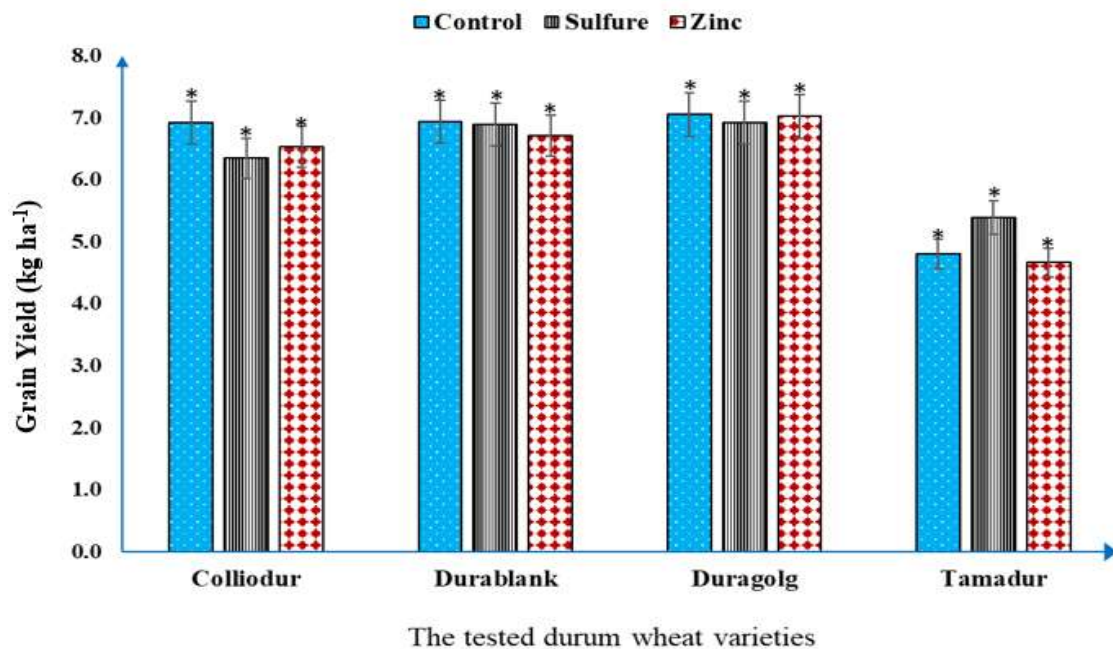


Figure 9. Effects of foliar-based zinc and sulfur fertilization on grain yields of different durum wheat varieties under the environmental conditions of the 2021 cropping season, Debrecen-Látókép. Bars indicated with single asterisks are statistically significant at 0.05%.

The results further indicate the importance of proper sulphur fertilizer application, especially under drought conditions, and highlight its interaction with environmental

factors to optimize grain yield. While sulphur fertilization may not fully counteract the adverse effects of drought stress on grain yield, it can alleviate its severity, suggesting that sulphur-based fertilization is beneficial, particularly in water-limited environments. This can be attributed to sulphur's role in enhancing photosynthetic rates and promoting the translocation of photosynthates to the grain sink (Raza et al., 2018). These results emphasize the need for an integrated nutrient management strategy, as relying on a single nutrient approach may not yield the desired outcomes.

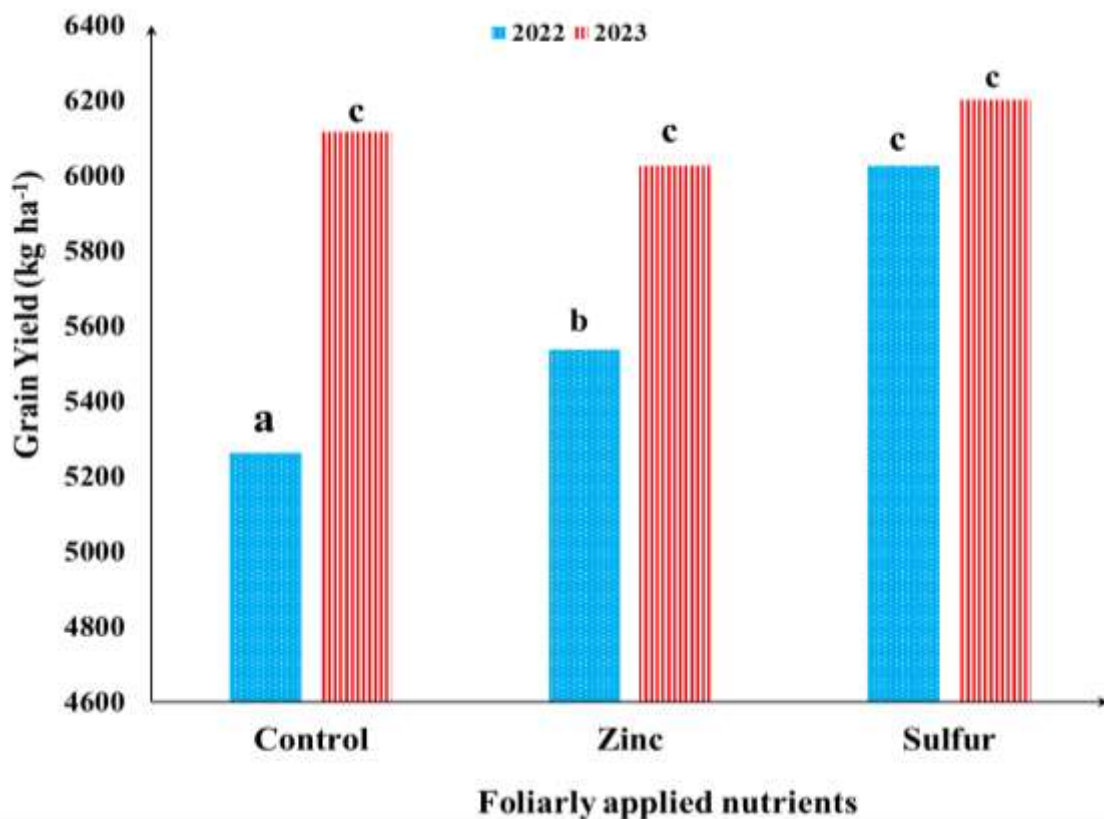


Figure 10. Interaction effect of growing season and foliar nutrient application (i.e. zinc and sulphur) on grain yield, Debrecen-Látókép, 2022-2023 cropping season. Bars with the same letter indicate no significant difference between treatment groups, while bars with different letters show significant differences.

The analysis of variance demonstrated that the effectiveness of zinc and sulphur fertilization in improving grain yield was significantly ($p < 0.05$) influenced by pedoclimatic conditions of the specific cropping seasons. In 2022, both zinc and sulphur demonstrated significant positive impacts on grain yield, with zinc improving yield by about 5.25% and sulphur by 14.52% (Figure 10). However, in 2023 cropping season, although grain yields were higher with zinc and sulphur application, the statistical difference was non-significant ($p < 0.05$) (Figure 10). This lack of statistical significance

suggests that environmental variables, such as rainfall, temperature fluctuations, or soil conditions, may have influenced the yield response, indicating the need for adaptive nutrient management strategies that account for specific growing conditions. The inconsistency in yield response across seasons suggests that relying solely on nutrient supplementation without considering pedoclimatic influences may limit potential yield gains. Hence, fine-tuning nutrient applications to match specific environmental conditions and cropping seasons could optimize both productivity and nutrient efficiency in durum wheat production.

The interaction between varieties, nutrient applications, and growing seasons significantly ($p < 0.05$) influenced grain yield (Table 3). In the 2023 cropping season, the highest grain yield was achieved with MV Pelsodur when treated with sulphur (8558.22 kg ha⁻¹) and zinc (8464.74 kg ha⁻¹). This suggests that MV Pelsodur benefited from these nutrients' roles in enhancing metabolic processes and improving stress tolerance, which was particularly effective under the favourable climatic conditions of 2023. In contrast, during the 2022 cropping season, MV Vékadur attained the maximum grain yield of 7540.24 kg ha⁻¹ with foliar sulphur fertilization, while zinc application yielded 6970.35 kg ha⁻¹ (Table 4). This indicates that the response of MV Vékadur to nutrient treatments differed from MV Pelsodur, potentially due to variations in growing conditions or differences in nutrient utilization mechanisms. The observed variation in nutrient effectiveness between the two growing seasons can be attributed to differences in pedoclimatic conditions of the growing location. The higher rainfall and optimal temperatures during the 2023 season likely facilitated better nutrient uptake and utilization, enhancing the benefits of sulphur and zinc applications. The 2022 season presented more challenging growing environment, characterized by lower rainfall and higher temperatures, where sulphur fertilization played a crucial role in supporting plant growth and yield.

In this context, nutrient applications such as sulphur and zinc may have been more effective in improving grain yield during one season due to specific climatic or soil conditions that favoured the applied nutrients availability and uptake efficiency. These results suggest that nutrient management should be designed to both the specific durum wheat variety and the prevailing environmental conditions to maximize grain yield. Variety MV Pelsodur, for instance, may benefit from the applied sulphur and zinc fertilizers under conditions similar to those in 2023, which possibly included higher

rainfall and optimal temperatures. In contrast, MV Vékadur might require different nutrient management strategies based on the conditions of the 2022 season, characterized by lower rainfall and higher temperatures. Hence, modifying nutrient applications to these specific environmental conditions and varietal responses can enhance durum wheat productivity and optimize resource use. Given the physiological roles of the applied nutrients, sulphur is known to enhance chlorophyll synthesis and improve overall plant metabolism, while zinc is essential for enzyme function and growth regulation (Melash et al., 2023).

Table 4. A combined effect of foliarly applied nutrients, cropping year and genetic landscape on grain yield formation of durum wheat varieties

GH	Varieties	Cropping Season					
		2022			2023		
		Control	Sulphur	Zinc	Control	Sulphur	Zinc
Winter	GK Bétadur	4978 ^{defgh}	5748 ^{klmnop}	4449 ^{abc}	6199 ^{opqrstu}	4581 ^{bcde}	5159 ^{fghij}
	GK Julidur	5781 ^{lmnop}	6746 ^{uvw}	5466 ^{hijklm}	5922 ^{mnopqr}	6402 ^{rstuv}	5445 ^{hijklm}
	MV Hundur	5569 ^{ijklmn}	6660 ^{tuvw}	6266 ^{opqrstu}	6373 ^{qrstu}	6729 ^{uvw}	6062 ^{nopqrs}
	MV Pelsodur	6014 ^{mnopqrs}	7089 ^{wx}	6706 ^{uvw}	7986 ^{yz}	8558 ^A	8465 ^{Za}
	MV Pennedur	5851 ^{lmnopqr}	7063 ^{wx}	6394 ^{rstuv}	6777 ^{uvw}	5870 ^{lmnopqr}	6545 ^{stuvw}
	MV Vékadur	6252 ^{opqrstu}	7540 ^{xy}	6970 ^{vw}	6082 ^{nopqrst}	5938 ^{mnopqr}	5795 ^{lmnopq}
Spring	Durablank	4326 ^{abc}	4628 ^{bcdef}	4915 ^{defgh}	4679 ^{bcdef}	5179 ^{fghijk}	5084 ^{efghi}
	Duragold	4457 ^{abcd}	4814 ^{cdefg}	4697 ^{bcdef}	5722 ^{ijklmno}	6319 ^{pqrstu}	5850 ^{lmnopqr}
	Tamadur	4121 ^{ab}	3932 ^a	3972 ^a	5307 ^{ghijkl}	6224 ^{opqrstu}	5817 ^{lmnopqr}
LSD_{0.05}		589	589	589	589	589	589
CV (%)		5.8	5.8	5.8	5.8	5.8	5.8

Among the spring-sown varieties, the maximum grain yield was achieved with Duragold, which reached 6319.18 kg ha⁻¹ following foliar application of sulphur during the 2023 cropping season (Table 4). This was followed by Tamadur, which yielded 6224.19 kg ha⁻¹ under similar conditions. In contrast, Tamadur had a significantly lower yield of 3932.02 kg ha⁻¹ in the 2022 season, even with sulphur application (Table 4). This represents a 58.295% enhancement in grain yield from 2022 to 2023 for Tamadur. The substantial yield increase for Duragold with sulphur application in 2023 indicates that sulphur was particularly beneficial for this variety under the conditions of that season. The lower yield of Tamadur in 2022 despite sulphur application suggests that other factors, beyond sulphur, might have influenced its performance. The variation in yield between seasons may be attributed to several factors. Sulphur is known to enhance various physiological processes, including protein synthesis and enzyme function, which are crucial for grain development (Klikocka et al., 2016). However, its effectiveness can be influenced by

seasonal factors such as soil nutrient availability, weather conditions, and overall plant health.

Table 5. The influence of genetic landscape, nitrogen application rate, and foliar application of nutrients (zinc and sulphur) on grain yield and spike density formation.

N rate (kg ha ⁻¹)	Varieties	GY (kg ha ⁻¹)			SPD (spikes/m ²)		
		Cont.	S	Zn	Cont.	S	Zn
60	GK Bétadur	6157.68	5348.48	5606.23	523.3	532.7	520.0
	GK Julidur	6639.24	6350.91	6059.18	512.0	490.7	516.7
	MV Hundur	6403.65	6713.04	6413.99	475.3	513.3	509.3
	MV Pelsodur	7232.09	7638.46	7631.62	474.7	457.3	480.0
	MV Pennedur	6743.59	6189.11	6225.58	495.3	493.3	501.3
	MV Vékadur	6369.07	6311.04	6690.10	497.3	522.7	514.7
	Durablank	4101.09	4775.46	4899.73	349.3	344.0	331.3
	Duragold	4720.04	5340.67	5209.38	346.0	304.0	394.0
	Tamadur	4171.82	4307.27	4265.00	371.3	393.3	349.3
100	GK Bétadur	5019.62	4980.40	4001.34	395.3	374.0	340.0
	GK Julidur	5063.94	6797.14	4851.26	517.3	530.0	533.3
	MV Hundur	5538.83	6675.87	5913.90	478.0	540.0	486.7
	MV Pelsodur	6768.47	8009.04	7539.44	479.3	461.3	498.0
	MV Pennedur	5884.72	6743.68	6713.29	498.7	492.0	565.3
	MV Vékadur	5965.24	7167.69	6075.47	563.3	540.0	549.3
	Durablank	4903.17	5031.79	5100.16	374.0	378.7	394.7
	Duragold	5458.32	5792.33	5337.48	508.0	456.0	490.7
	Tamadur	5255.71	5848.94	5523.7	398.0	400.0	376.0
LSD 0.05		503.44	503.44	503.44	10.96	10.96	10.96
CV (%)		5.8	5.8	5.8	1.3	1.3	1.3

The interaction effect between varieties, nitrogen application rate, and foliar nutrient application was statistically significant ($p < 0.05$) for grain yield (Table 5). The effectiveness of the applied nutrients, however, varied significantly depending on the genetic landscape of the tested varieties. The maximum grain yield was achieved with a combination of high nitrogen rate and foliar applications of sulphur (8009.04 kg ha⁻¹) and zinc (7539.44 kg ha⁻¹) for the variety MV Pelsodur. This was followed by MV Vékadur, which yielded 7167.69 kg ha⁻¹ under high nitrogen and sulphur fertilization. In contrast, varieties such as GK Bétadur and GK Julidur attained maximum grain yield under low nitrogen application without additional nutrients like zinc or sulphur. For GK Bétadur, the grain yield with low nitrogen alone was 15.13% higher compared to low nitrogen combined with sulphur, while GK Julidur showed similar trends. This means that the added sulphur did not enhance yield compared to low nitrogen alone.

These results indicate that while the interaction of nitrogen and foliar nutrients was crucial, the genetic traits of the varieties played a significant role in their responsiveness to these treatments. The high yields achieved with MV Pelsodur and MV Vékadur suggest that these varieties may be particularly well-adapted to utilize sulphur and zinc effectively when combined with high nitrogen rates. In contrast, GK Bétadur and GK Julidur may perform optimally with less nutrient input. This highlights the importance of considering both the variety and nutrient management strategies to optimize grain yield. These interactions can therefore guide targeted nutrient application practices to enhance durum wheat productivity.

While the interaction of nitrogen rate and foliar nutrients contributed to yield increases, the combined effect of cropping season, variety, and foliar nutrients showed a more substantial yield improvement (Table 5). It has been evidenced that, the yield enhancement from the interaction between cropping season, varieties, and foliar nutrients was 42.3031% greater for variety MV Pelsodur under sulphur fertilization in under favourable environment than that observed with nitrogen and foliar nutrients alone which improves grain yield by 18.39% under high nitrogen application environment. This suggests that environmental factors and their interactions with crop varieties and nutrient applications play a more critical role in determining yield than the combined effect of nitrogen and foliar treatments.

4.1.4. Nutrient Antagonism and Synergism Effects on Grain Yield enhancement

When evaluating the main effects of nitrogen (N) and sulphur (S) individually compared to their combined interaction, the yield variation attributable to sulphur (5790.19 kg ha⁻¹) application alone versus a high nitrogen rate (5856.58 kg ha⁻¹) was minimal, showing only a slight difference of 1.13% (Table 7). This suggests that the individual effects of sulphur or high nitrogen alone on grain yield were relatively modest. However, a substantial increase in yield, ranging from 8.24% to 9.48%, was observed with the co-application of sulphur and high nitrogen (Figure 11). This significant yield increment indicates a clear synergistic effect, where the combined application of N and S resulted in a yield response that far exceeded the sum of their individual effects. This lack of an additive effect highlights the importance of co-fertilization with both N and S to fully realize the yield potential in durum wheat. These results are consistent with previous research indicating that the combined application of high N and sulphur S fertilization

enhances nutrient uptake and yields more effectively than individual applications (Dawar et al., 2022).

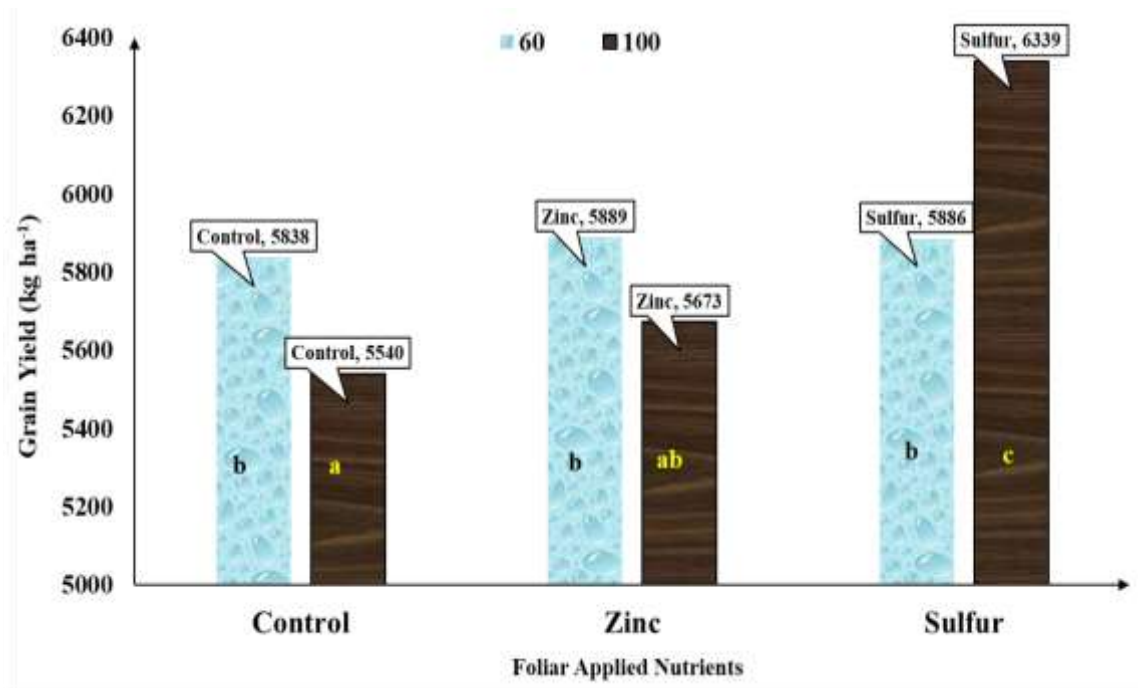


Figure 11. The interactive effect of varying nitrogen application rates (**60 and 100 kg ha⁻¹**) and the addition of nutrients (**zinc and sulphur**) on grain yield, Debrecen-Látókép, 2022-2023 cropping season. Treatments sharing the same letter are not significantly different from each other ($p < 0.05$), whereas treatments with different letters exhibit statistically significant differences.

Research has shown that sulphur application in wheat can enhance nitrogen use efficiency (NUE) by up to 50% and nitrogen recovery efficiency by 60% (Mustafa et al., 2022). This sulphur-nitrogen synergy positively impacts grain yield and quality by optimizing nitrogen metabolism (Roa et al., 2024). The benefits of sulphur are especially pronounced at higher nitrogen levels, where it helps to mitigate issues such as nutrient imbalances and diminished NUE. Klikocka et al. (2016) reported that co-application of sulphur and nitrogen increases the levels of essential amino acids like cysteine and methionine in wheat grain. These amino acids, crucial for protein synthesis, represent nearly 90% of the sulphur found in plants (Aula et al., 2019). Our observations also align with this pattern, showing a significant yield increase when sulphur and nitrogen are applied together, indicating the importance of an integrated fertilization strategy. This integrated approach moves beyond simple additive models of nutrient application, embracing a more sophisticated understanding of nutrient interactions to optimize crop productivity and quality.

Table 6. The influence of integrated nutrient supply and varietal difference on grain yield formation of durum wheat varieties under contrasting cropping season

N Rate (kg ha ⁻¹)	Varieties	2022			2023		
		Control	Sulphur	Zinc	Control	Sulphur	Zinc
60	GK Bétadur	5789.94	5910.88	6004.18	6525.41	4786.08	5208.29
	GK Julidur	6307.11	6629.79	6280.12	6971.36	6072.03	5838.25
	MV Hundur	5199.73	6740.87	6539.86	7607.56	6685.21	6288.12
	MV Pelsodur	5511.38	6828.67	6895.88	8952.81	8448.25	8367.35
	MV Vékadur	5985.73	7126.45	6764.21	6752.41	5495.62	6615.98
	Durablanck	3943.42	4507.73	4826.81	4258.76	5043.19	4972.65
	Duragold	4163.67	4360.17	4489.31	5276.41	6321.18	5929.44
	Tamadur	3740.91	2778.17	3245.48	4602.73	5836.37	5284.51
100	GK Bétadur	4165.80	5585.48	2893.27	5873.44	4375.33	5109.40
	GK Julidur	5254.71	6862.78	4651.64	4873.16	6731.50	5050.87
	MV Hundur	5938.38	6578.76	5991.73	5139.28	6772.97	5836.07
	MV Pelsodur	6516.79	7349.89	6516.77	7020.15	8668.20	8562.12
	MV Pennedur	5845.44	7467.59	6193.92	5924.00	6019.77	7232.66
	MV Vékadur	6518.69	7954.03	7176.49	5411.79	6381.36	4974.46
	Durablanck	4707.62	4748.71	5004.02	5098.72	5314.87	5196.30
	Duragold	4749.47	5267.48	4905.15	6167.18	6317.17	5769.81
Tamadur	4500.93	5085.87	4698.35	6010.48	6612.01	6349.05	
LSD_{0.05}		825.543	825.543	825.543	825.543	825.543	825.543
CV (%)		8.90	8.90	8.90	8.90	8.90	8.90

The interaction between a high nitrogen rate (100 kg ha⁻¹) and zinc foliar application also demonstrated complex effects on grain yield. When zinc was combined with a low nitrogen rate of 60 kg ha⁻¹, the grain yield increased to 5889 kg ha⁻¹ (Figure 11). This result is consistent with previous studies, which have shown that optimal soil nitrogen levels combined with foliar zinc application, along with the use of suitable cultivars, can enhance grain yield (Xia et al., 2018). In comparison, applying zinc alone led to a more substantial yield increase, reaching 6112.30 kg ha⁻¹, an approximate 3.79% improvement over the zinc and low nitrogen combination. Remarkably, the combined application of zinc with a high nitrogen rate did not result in a higher grain yield than zinc alone. Instead, this combination led to a lower yield, with a negative yield impact of -3.67% compared to the yield achieved with zinc alone (Figure 10). The antagonistic effect of zinc on grain yield when applied alongside other fertilizers, such as phosphorus, has been documented in various crops (Aboyeji et al., 2020).

These results indicate that while zinc alone can significantly enhance grain yield, its beneficial effects are diminished when combined with high nitrogen rates. The negative yield impact observed when zinc is combined with high nitrogen suggests a potential antagonistic interaction between these two nutrients at elevated nitrogen levels. This highlights the importance of carefully balancing nutrient inputs to avoid negative interactions that can reduce durum wheat productivity. This antagonism could be due to several factors, including nutrient competition or metabolic imbalances within the plant. It has been previously reported that applying higher rates of nitrogen fertilizer can adversely affect the absorption and utilization of essential nutrients, leading to reductions in both yield and quality (Singh et al., 2018). When nitrogen levels are higher but zinc is insufficient—especially if not adequately replenished—the concentration of zinc in the grain decreases (Singh et al., 2018).

The synergistic effect of nitrogen application combined with sulfur fertilization on grain yield was significantly ($p < 0.05$) influenced by the application rate, cropping season, and varietal differences (Table 6). In particular, variety MV Pelsodur achieved its highest grain yield of 8952.81 kg ha⁻¹ under a low nitrogen rate of 60 kg ha⁻¹ during the 2023 cropping season without additional foliar nutrients such as zinc or sulfur (Table 6). This suggests that MV Pelsodur can be highly efficient under lower nitrogen conditions. In contrast, MV Pelsodur also recorded a relatively high yield of 8668.20 kg ha⁻¹ under a high nitrogen rate with sulfur fertilization, though this was not as high as its yield under low nitrogen conditions. In the 2022 cropping season, varieties such as MV Vékadur (7954.03 kg ha⁻¹) and MV Pennedur (7467.59 kg ha⁻¹) performed significantly better under application of high nitrogen rates and sulphur fertilization compared to the 2023 cropping season (Table 6). This suggests that the effectiveness of nutrient applications can vary based on environmental conditions, such as soil nutrient availability and weather patterns.

While MV Pelsodur demonstrated high yields under low nitrogen with minimal nutrient additions, it also showed improved performance with higher nitrogen and sulphur applications under specific conditions. The variations in yield across different treatments suggest that while some varieties may excel under specific conditions, others may require a combination of high nitrogen and foliar nutrients for maximum productivity. These results further highlight the need for targeted nutrient management strategies that consider both genetic characteristics and environmental factors to enhance durum wheat yield.

The positive response of both winter- and spring-sown durum wheat varieties to the combined application of nitrogen and sulfur indicates the potential of this nutrient combination to enhance grain yield across different growing seasons. The spring-sown variety Tamadur achieved its highest grain yield when 100 kg ha⁻¹ of nitrogen was applied in combination with sulfur fertilization, with yields increasing from 5836.37 kg ha⁻¹ to 6612.01 kg ha⁻¹—a 13.29% improvement compared to the yields achieved with a lower nitrogen rate combined with sulfur (Table 6). This suggests that sulphur fertilization, when paired with higher nitrogen levels, is more effective in enhancing grain yield than when used with lower nitrogen rates. These results align with existing research that emphasizes sulphur's critical role in improving wheat grain yield, particularly when nitrogen is adequately supplied (Sharma et al., 2024).

The increased grain yield in Tamadur can be attributed to several factors associated with sulphur's role in improving nitrogen use efficiency. This combination allows the plant to more effectively use nitrogen, leading to improved growth and higher grain production (Klikocka and Marks, 2018). In addition to enhancing nitrogen metabolism, sulphur may improve the crop's resilience to environmental stressors including drought. It can support drought tolerance by reducing stomatal openings, boosting proline accumulation, and strengthening antioxidant defences mechanism, which collectively contribute to yield stability under suboptimal growing conditions (Han et al., 2019). While these results offer valuable insights into optimizing nutrient management, further research is necessary to explore the underlying mechanisms behind the nitrogen-sulfur interaction. Additionally, evaluating the consistency of these benefits across different durum wheat varieties and agroecological zones will be essential to refining nutrient strategies for varying environments.

Another critical factor that significantly affected the grain yield was the interaction effect between the combined application of zinc, sulphur, and nitrogen rate, along with the varying moisture status of the growing seasons (Figure 12). These interactions indicate the complexity of nutrient dynamics and their influence on durum wheat performance under different environmental conditions. In the 2022 dry season, relatively highest grain yield (6322 kg ha⁻¹) was achieved with a high nitrogen rate combined with sulphur application. This suggests that under drought conditions, the combined application of sulphur and high nitrogen was crucial for optimizing grain yield, possibly due to sulphur's role in nitrogen use efficiency. On the contrary, in the 2023 cropping season, which

experienced more favourable moisture conditions, the highest grain yield (6509 kg ha⁻¹) was attained with a 60 kg ha⁻¹ nitrogen rate without additional sulphur or zinc (Figure 12). This indicates that in a wetter year, moderate nitrogen application alone was sufficient to achieve high grain yield, and the additional sulphur and zinc did not provide a significant yield benefit. This could be due to better overall nutrient availability and uptake in the wetter conditions, reducing the need for supplemental nutrient applications.

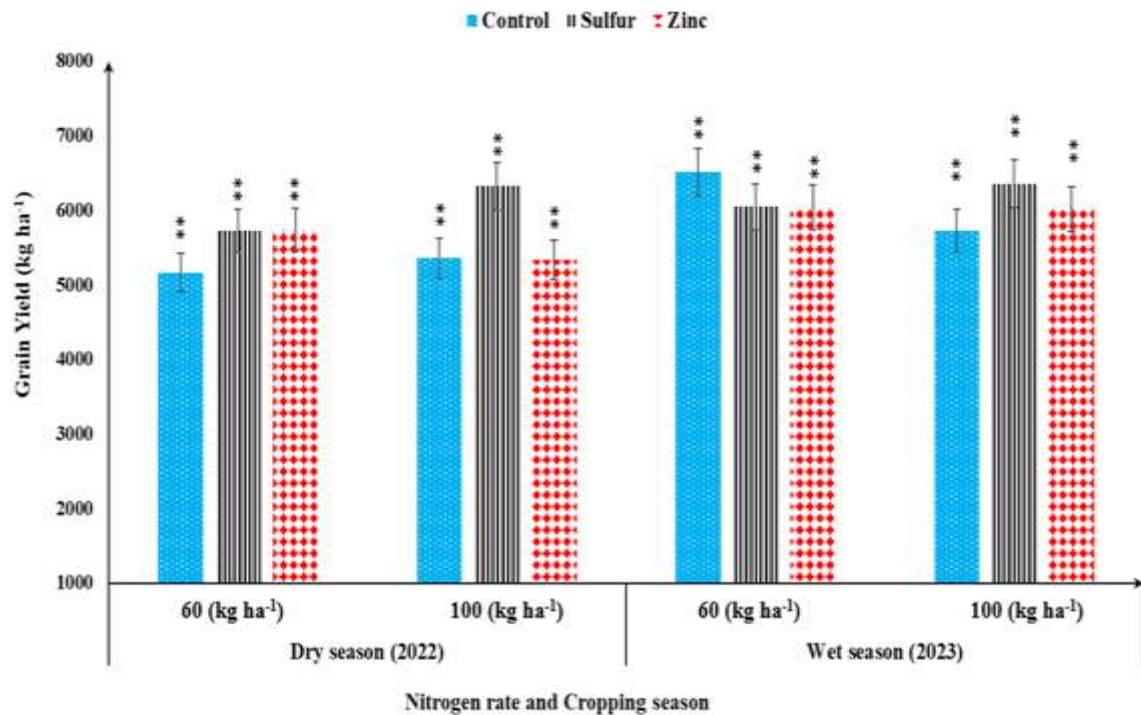


Figure 12. The relationship between foliar-based zinc and sulphur fertilization, including their interaction with variable nitrogen rates, on grain yield across different growing seasons. Bars indicated with double asterisks are statistically significant at 0.01%. The 2022 season is characterized as dry, while the 2023 season is characterized as wet, Debrecen-Látókép.

As revealed by this analysis, it can be universally concluded that nutrient management strategies for durum wheat should be adjusted to both the genetic characteristics of the varieties and the specific pedoclimatic conditions of the growing season. Although yield outcomes varied across different growing seasons, the variety MV Pelsodur consistently achieved its maximum grain yield under both high and low nitrogen environments. This indicates that MV Pelsodur is a versatile variety suitable for environments where water scarcity is not a major concern. In the wet 2023 cropping season, MV Pelsodur reached its highest grain yield with a low nitrogen application rate of 60 kg ha⁻¹, without the need

for additional nutrient supplements. This highlights its efficiency and adaptability, making it an excellent choice for cultivation in regions with similar conditions.

4.2. The Effect of Nutrient Management and Genetic Variation on Yield Associated Metrics: Fine-Tuning Durum Wheat Agronomy

4.2.1. Effect of Nutrient Application and Varietal Differences on Spike Density

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 (SPD) per square meter (Table 7). However, the main effect of nitrogen application rate alone did not show a statistically significant ($p < 0.05$) impact on spike density (Table 7). The significant interactions between the imposed factors imply that the formation of adequate spike density response to nitrogen application varies depending on the variety and the additional nutrients applied (Table 8). 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. This could be due to factors such as nutrient saturation, where additional nitrogen does not further benefit the durum wheat varieties, or the presence of other limiting factors such as water availability or soil health.

The evaluation of nitrogen application rates revealed significant ($p < 0.001$) variability in spike density 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 7). The enhanced ability of these varieties to utilize nitrogen effectively for spike development and growth suggests they likely have higher nitrogen use efficiency, a trait that has been positively correlated with improved yield outcomes. This positive response to increased nitrogen is consistent with results from several studies, which have shown that adequate nitrogen supply can significantly enhance spike number and overall yield in wheat (Jamaati-e-Somarin et al., 2010).

Table 7. 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)	PH (cm)	GPC (%)	GY (kg ha ⁻¹)	
N (kg ha ⁻¹)	60	452.29	5.95	77.67	14.98	5870.87	
	100	467.29	6.59	79.30	15.46	5856.58	
	LSD _{0.05}	25.85	0.27	3.31	1.11	143.58	
	CV (%)	1.60	1.20	1.20	2.10	0.70	
Nutrients	Control	458.69	6.18	77.73	15.15	5688.68	
	Zinc	456.87	6.29	79.12	15.28	6112.30	
	Sulphur	463.89	6.34	78.61	15.23	5790.19	
	LSD _{0.05}	4.67	0.16	0.84	0.15	226.05	
	CV (%)	2.59	4.80	2.80	3.50	2.90	
Varieties	Winter	GK Bétadur	505.10	6.59	77.27	15.58	5185.63
		GK Julidur	516.70	5.81	74.07	15.83	5960.28
		MV Hundur	500.40	7.09	87.43	15.36	6304.32
		MV Pennedur	469.80	6.77	84.99	15.07	6416.66
		MV Vékadur	513.00	6.11	85.70	15.07	6429.77
		MV Pelsodur	531.20	7.59	86.81	14.32	7469.85
	Spring	Durablank	355.70	5.46	69.88	15.58	4801.90
		Duragold	365.20	5.46	70.33	15.38	5309.70
		Tamadur	381.30	5.55	69.90	14.80	4895.40
		LSD _{0.05}	12.29	0.44	3.770	0.63	292.710
CV (%)	2.30	6.00	4.10	2.60	7.50		

Key to abbreviations: PH (cm): Plant height, SPL (cm): Spike length, SPD (m²): Spike density, GPC (%): Grain protein content, GY (kg ha⁻¹): Grain yield, LSD_{0.05}: Least significant difference, CV (%): Coefficient of variation

In contrast, the spring-sown variety Tamadur recorded the lowest spike production (391.3 spikes/m²) even with the high nitrogen rate (Table 2). This result aligns with research indicating that different wheat varieties can have varying optimal nitrogen requirements and that some varieties may not benefit as much from excessive nitrogen application (Melash et al., 2023). This suggests that Tamadur may not benefit as much from increased nitrogen rate, potentially due to a different nutrient optimization strategy or inherent physiological constraints. It may also reflect a lower capacity to efficiently utilize excess nitrogen, as suggested by studies showing that excessive nitrogen can lead to imbalances and reduced nutrient uptake efficiency (Wang et al., 2021).

The lower spike density observed in Tamadur could be due to either its inherently limited tillering capacity or a lower responsiveness to nitrogen inputs. Research has shown that increasing spike density is often associated with significant genetic improvements in the

production of fertile tillers (Boussakouran et al., 2021). Thus, enhancing spike density could be achieved by selecting and breeding durum wheat varieties that are more capable of utilizing resources efficiently to produce additional tillers. Investigating how these varieties manage nitrogen and adapt to varying nitrogen levels could lead to more precise recommendations for fertilization practices and contribute to breeding programs aimed at developing varieties with optimized spike density. Interestingly, some varieties, such as GK Bétadur, exhibited higher spike production under lower nitrogen rates compared to higher N rates (Table 7). This implies that GK Bétadur, and potentially other similar varieties, may be more efficient or optimized at lower nitrogen levels. This suggests that nitrogen application can increase the number of spikes per square meter in durum wheat, although this might occur at the expense of tillering potential in certain varieties.

However, analysis of spike production in relation to grain yield revealed an unexpected pattern. Varieties exhibiting the highest spike densities did not consistently produce the highest grain yields (Table 2 and 7). MV Pelsodur, for instance, achieved the maximum grain yield of 7438.99 kg ha⁻¹ despite possessing the lowest spike density (479.60 spikes/m²) under 100 kg ha⁻¹ (Table 2). In contrast, MV Vékadur, GK Julidur, and MV Hundur, characterized by higher spike densities (550.90, 526.90, and 501.60 spikes/m², respectively), yielded significantly lower grain yields (6402.80, 5570.78, and 6098.42 kg ha⁻¹) under high nitrogen conditions (Table 2). An intriguing observation emerged with GK Bétadur, the lowest yielding winter-sown variety. This variety demonstrated that maximum spike production under low nitrogen conditions resulted in a relatively higher grain yield compared to high-nitrogen environments (Table 2). This trend was also evident in spring-sown varieties. A substantial phenotypic variation in spike density was observed, with Tamadur (381.30 spikes/m²) exhibiting the highest density followed by Duragold (365.20 spikes/m²), despite its high yielding potential. In contrast, Durablank showed the lowest spike density at 355.70 spikes/m² (Table 7).

The ability of varieties such as MV Pelsodur to achieve high yields despite lower spike density may be attributed to its greater spike length under high nitrogen environment (Table 2 and 7). The contrasting behaviour of GK Bétadur under different nitrogen regimes suggests that nitrogen application rates should be optimized to avoid detrimental effects on yield, even if spike production is high. This result highlights the need for precise nutrient management to maximize grain yield. The substantial phenotypic variation in spike density among spring-sown varieties indicates the potential for genetic

improvement in this trait. However, it is crucial to consider the relationship between spike density and other yield components to avoid selecting for varieties with high spike density but low grain yield. These results suggest that while high spike production (spikes/m²) can increase the number of potential grain-bearing structures, it does not necessarily translate to a higher total harvestable yield. This further indicates that spike density alone may not be a sufficient predictor of grain yield. A balanced approach that optimizes multiple yield components, rather than solely focusing on increasing spike density, is likely to be more effective in achieving sustainable and high-yielding durum wheat varieties. It is crucial to consider the interaction between spike density and other yield components, such as spike length, grain number per spike, and other physiomorphological traits.

The non-linearity between spike density and grain yield indicates the complex interaction of genetic, environmental, and management factors. Variations in tillering potential, phenological plasticity, and maturity period length, particularly under water-limited conditions, may contribute to this complexity. However, an overall reduction in the number of spikes under variable climatic conditions has been reported, suggesting that environmental stress can diminish spike production regardless of a variety's stay-green traits (Lin et al., 2020). High spike density can intensify competition for resources such as light, water, and nutrients, potentially compromising grain filling and overall yield. This resource competition is particularly critical during the grain-filling period when the demand for nutrients and water is high. In environments with limited resources, high spike density may lead to smaller grain size and reduced yield despite the higher number of spikes. Nitrogen management plays a crucial role in this dynamic. While nitrogen is essential for plant growth, excessive application can lead to an imbalance between vegetative and reproductive development, resulting in higher spike density but lower grain yield. This is because excessive vegetative growth can divert resources away from grain filling. Precision nitrogen management is therefore very important to optimize grain yield while ensuring resource efficiency.

The interaction between nitrogen rate, varieties, and foliar nutrient application significantly ($P < 0.001$) influenced SPD (Table 5). The maximum SPD was recorded in MV Pennedur (565.3 spikes/m²) when a high nitrogen rate was combined with zinc fertilization. This was followed closely by MV Vékadur, which produced 563.3 spikes/m² under high nitrogen application alone, and showed similar high SPD when high nitrogen

was combined with foliar zinc fertilization. However, responses to nutrient applications varied among other varieties. Varieties such as GK Bétadur achieved a maximum spike density of 532.7 spikes/m² when a low nitrogen rate (60 kg ha⁻¹) was combined with foliar sulfur fertilization (Table 5). This suggests that GK Bétadur may be more efficient in utilizing sulfur for spike production, even at lower nitrogen levels.

While high nitrogen coupled with foliar zinc application positively influenced spike density in varieties like MV Pennedur and MV Vékadur, the contrasting performance of GK Bétadur under lower nitrogen and sulphur conditions emphasizes the necessity of cultivar-specific nutrient management. These results highlight the importance of adjusting nutrient management strategies to the specific genetic and physiological needs of each variety to optimize spike density and overall yield. The positive response of certain durum wheat varieties to foliar zinc application at the flag leaf stage is particularly noteworthy. This critical growth period is characterized by rapid grain filling, and enhanced photosynthesis through zinc supplementation can directly contribute to increased yield. However, it is essential to consider that zinc efficacy is cultivar-dependent, and indiscriminate application may not be economically viable or environmentally sound.

The emphasis on the importance of sulphur in certain varieties adds another layer of complexity to nutrient management. Its role in improving spike density implies that sulphur deficiency could lead to losses in productive spikes and decreased grain yield consequently. These insights provide valuable guidance for agronomists and durum wheat breeders in selecting appropriate varieties and nutrient management plans adjusted to specific environmental conditions. In regions where soil zinc levels are low, selecting varieties including MV Pennedur and applying foliar zinc at the flag leaf stage could significantly boost yield. In areas with sulphur-deficient soils, varieties such as GK Bétadur might perform better with sulphur supplementation and a more conservative nitrogen application.

4.2.2. Influence of Nutrient Application and Varietal Difference on Spike Length

The spike length of durum wheat is a significant factor in determining grain number and ultimately harvestable yield. However, this trait is influenced by both genetic and environmental factors, including nutrient availability. In the current study, the length of the spike was significantly ($p < 0.05$) influenced by the interaction between nitrogen

application rate and varietal difference. In winter sown durum wheat varieties, the maximum spike length was observed for variety MV Pelsodur (at high N 7.72 cm; 7.14 cm at low N) followed by MV Vékadur (at high N 7.12 cm; 7.07 cm at low N) under both high and low nitrogen application rate. In contrast the spring sown varieties such as Tamadur (6.57 cm), followed by Durablank (6.47 cm) perform maximum spike length under high nitrogen environment than low nitrogen application rate (Table 2). These results suggest that winter-sown varieties may have a more stable spike length across different nitrogen levels, potentially due to their longer growth period, which allows for more consistent nutrient absorption. On the other hand, spring-sown varieties may be more responsive to increased nitrogen, resulting in greater spike elongation when nutrients are abundant. Higher nitrogen rates enhance nutrient uptake and support cell division and elongation during spike development, leading to longer spikes. However, understanding these interactions can help in optimizing nutrient management strategies to maximize spike length and overall crop productivity.

Nutrient application was found to be a critical factor influencing spike length in durum wheat, with nitrogen application rate, foliar nutrient application, and varietal differences all playing significant roles ($p < 0.05$; Table 7). Increased nitrogen application resulted in longer spikes, with the maximum spike length of 6.59 cm observed at higher nitrogen rates, compared to 5.95 cm at lower rates. This suggests that higher nitrogen availability enhances spike development by promoting cell division and elongation, as well as overall plant growth. Additionally, foliar nutrient applications and varietal differences also significantly impacted spike length, with some varieties responding more favorably to nutrient inputs than others. These results indicate the importance of tailored nutrient management strategies that consider both the specific variety and environmental conditions to optimize spike length and, ultimately, durum wheat productivity.

The interaction between genetic differences and foliar nutrient applications significantly influenced spike length in durum wheat varieties (Table 8). Application of zinc-containing fertilizers resulted in the longest spikes, with MV Pelsodur reaching 7.58 cm and MV Vékadur achieving 7.21 cm. This effect was similarly observed with sulphur application, where MV Pelsodur and MV Vékadur also exhibited increased spike lengths. In contrast, MV Hundur achieved its maximum spike length of 6.86 cm under sulphur fertilization, while zinc application resulted in a shorter spike length of 6.56 cm. These

results suggest that both zinc and sulphur can enhance spike length, but their effectiveness varies depending on the genetic characteristics of the durum wheat varieties.

Table 8. The interaction effect between foliar nutrient application and varietal difference on some selected agronomic traits

Varieties	PH (cm)			SPD (m ²)			SPL (cm)		
	Control	Sulphur	Zinc	Control	Sulphur	Zinc	Control	Sulphur	Zinc
GK Bétadur	77.73	76.47	77.60	515.70	494.30	505.30	6.16	6.65	6.95
GK Julidur	70.27	76.10	75.83	514.70	510.30	525.00	5.90	5.97	6.06
MV Hundur	87.80	86.30	88.20	476.70	526.70	498.00	6.89	6.86	6.56
MV Pelsodur	84.47	86.38	84.13	477.00	459.30	489.00	7.28	7.42	7.58
MV Pennedur	85.23	88.27	83.60	497.00	492.70	533.30	5.94	6.00	6.38
MV Vékadur	86.97	87.10	86.37	530.30	531.30	532.00	6.93	7.13	7.21
Durablank	69.43	70.00	70.20	372.30	359.00	335.70	5.38	5.60	5.41
Duragold	69.30	70.77	70.93	360.00	341.30	394.30	5.41	5.51	5.47
Tamadur	68.40	70.67	70.63	384.70	396.70	362.70	5.71	5.46	5.47
LSD _{0.05}	4.25	4.25	4.25	7.84	7.84	7.84	0.52	0.52	0.52
CV (%)	2.80	2.80	2.80	1.30	1.30	1.30	4.80	4.80	4.80

The observed increase in spike length with higher nitrogen rates is consistent with previous research highlighting nitrogen's importance for plant growth and development. Nitrogen is a fundamental component of proteins and nucleic acids, essential for cell division and elongation. Thus, its availability directly impacts the plant's ability to produce longer spikes. While the study focused on nitrogen, it is important to note that other nutrients (i.e., zinc and sulphur) and varietal factors also contribute to spike length variation. The application of either zinc or sulfur was found to be statistically significant ($p < 0.05$) in influencing spike length, with consistent effects observed across different genetic backgrounds. Foliarly-applied nutrients influenced spike length, with sulfur fertilization resulting in the maximum spike length of 6.34 cm. This was slightly greater than the 6.29 cm observed with zinc application and the 6.18 cm in the control group. The increase in spike length with sulfur application may be attributed to its role in enhancing protein synthesis and overall plant health.

Although the differences among treatments are minimal, sulfur application appears to have a marginally greater effect on spike length compared to zinc and the control. This finding suggests a potential advantage of sulfur in promoting spike development, though the practical significance of these small differences should be carefully considered in the broader context of nutrient management and cost-effectiveness. The marginal increase in spike length might have limited impact on overall yield, depending on the specific

environmental conditions and farming practices. Therefore, additional research is warranted to explore the underlying physiological mechanisms by which sulfur influences spike length and to evaluate the broader benefits of sulfur versus zinc across multiple mega environments and a larger genetic pool.

Another important factor determining spike length was the genetic differences and planting windows of the tested varieties. The analysis revealed that winter-planted varieties exhibited superior spike lengths, with MV Pelsodur achieving the longest spike length at 7.59 cm, followed by MV Hundur at 7.09 cm, and MV Pennedur at 6.77 cm. In contrast, spike lengths among spring-sown varieties, including Durablank, Duragold, and Tamadur, did not show statistically significant differences (Table 7). The observed genetic variation suggests that winter-planted varieties may possess inherent traits that favor greater spike development, potentially due to the influence of cooler temperatures, longer growing periods, or other seasonal factors that enhance spike formation. The lack of significant variation among spring-sown varieties could be attributed to a narrower range of genetic differentiation or more uniform environmental conditions during the spring growing season. These results indicate the potential advantages of selecting and breeding winter-planted varieties for improved spike length, which could lead to enhanced grain yield.

When considering the contribution of spike length to maximum grain yield, varieties with longer spikes were consistently observed to produce higher grain yields across various nutrient applications and growing seasons. The variety MV Pelsodur, which achieved the longest spike length (7.59 cm), translated this trait into the highest harvestable grain yield (Table 2). The longer spike length likely supported the development of more spikelets, leading to increased grain number and overall yield. This correlation emphasizes the importance of selecting for spike length in breeding programs aimed at maximizing durum wheat productivity.

4.2.3. Genotype × Environment Interaction in Determining Plant Height

Plant height is a critical trait that influences various aspects of crop growth, management, and productivity. The analysis of variance showed that the influence of foliar nutrient application and genetic differences was significantly impacted plant height (cm), whereas the main effect of nitrogen application rate did not show a significant influence. This suggests that while nitrogen is essential for overall plant growth, its effect on height may

be mediated by other factors such as genetic potential and foliar nutrient supplements. 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. However, other studies have reported similar findings, suggesting that nitrogen's influence on plant height might be more pronounced under specific environmental conditions or in combination with other factors. Hence, further research is needed to elucidate the mechanisms underlying the interaction between nitrogen application rate and plant height.

A significant variation in plant height was observed among winter-sown durum wheat varieties, 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). These results underline the substantial influence of genetic factors on plant height in winter-sown conditions. 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 7). 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 strategies. The lack of significant variation further suggests that environmental factors such as photoperiod and temperature fluctuations might override genetic potential for height in spring-planted varieties. These environmental factors may exert a stronger influence on plant development, potentially limiting the expression of genetic traits associated with taller growth. Hence, the varieties by environment interaction ($G \times E$) is crucial for optimizing plant height and overall productivity in different planting windows.

Variation in plant height was found to be significantly pronounced when the tested varieties were subjected to a combination of foliarly applied zinc and sulfur fertilizers, compared to the effects of the imposed factors individually. Among winter-planted varieties, the maximum plant height was observed in MV Pennedur under sulfur treatment (88.27 cm), followed closely by MV Hundur under zinc fertilization (88.20 cm) (Table 8). In contrast, the minimum plant heights were recorded in varieties like GK Julidur and GK Bétadur, regardless of whether zinc or sulfur was applied. While significant differences in plant height were attributed to the interaction between varietal genetics and foliar nutrient application, the differences between zinc and sulfur treatments themselves were not statistically significant across all varieties, with some exceptions. This suggests

that genetic factors play a more decisive role in determining plant height than the specific nutrient applied during the growing season.

The enhanced plant height in certain winter varieties with specific nutrient treatments implies that these nutrients may interact with genetic traits to promote growth. Sulfur, essential for amino acid and protein synthesis, and zinc, critical for enzyme function and hormone regulation, are likely contributors to these differences. However, in spring-planted varieties, including Durablank, Duragold, and Tamadur, no statistically significant differences in plant height were observed with zinc or sulfur fertilization. This lack of responsiveness may be due to the genetic makeup of these spring varieties, which could be less sensitive to foliar nutrient treatments. Additionally, different environmental conditions during the spring growing season, such as higher temperatures and longer daylight hours, might also reduce the impact of these treatments, further highlighting the complex interplay between genetics and environment in determining plant height.

The observed differences between winter-sown and spring-planted varieties on plant height could be due to genetic predispositions and environmental adaptations. Winter-sown varieties generally have longer growing periods and may experience different environmental conditions compared to spring-planted ones, which could contribute to the observed height differences. These results suggest that while foliar nutrient application and genetic selection are critical for optimizing plant height, the role of nitrogen application may vary depending on existing soil fertility and specific growth stages. Agronomists and policy makers should therefore consider these factors when selecting varieties and developing nutrient management strategies to enhance crop productivity. The identified genotypic differences in plant height emphasize the potential for genetic improvement through breeding programs. Selecting varieties with desirable plant height characteristics, can develop varieties that are better adapted to specific growing environments and less prone to lodging. The results emphasize the importance of considering both genetic and agronomic factors when developing crop management strategies aimed at optimizing plant architecture and yield.

4.3. Nitrogen Application and Its Effects on Physiological and Leaf Reflectance Indices of Durum Wheat Through Different Growth Stages and Seasons

4.3.1. SPAD Indices as Metrics for Nitrogen Application Effects: Temporal Variations and Developmental Stage Analysis

The nexus between nutrient availability and environmental influences on durum wheat growth and development is a critical area of research. This study utilizes SPAD readings to investigate the dynamic interaction between nitrogen availability and environmental factors in determining durum wheat growth and vitality. SPAD measures chlorophyll content, which serves as an indicator of plant health and nutrient status. The study revealed contrasting responses in chlorophyll content due to the interaction between growing season and nitrogen rate (Table 10). Significant difference ($p < 0.05$) were observed in chlorophyll levels across different nitrogen fertilization rates and developmental stages, highlighting how both nitrogen availability and environmental conditions impact durum wheat growth (Table 10). This statistical significant results suggest that optimizing nitrogen application could enhance durum wheat vitality, particularly when designed to specific growing conditions.

The SPAD values, which measure relative chlorophyll content, peaked at low nitrogen application rates during the booting and tillering stages but declined during the flowering stage in both cropping seasons (Table 14). Numerous studies have reported that SPAD values increase with plant age and subsequently decrease at the latter growth stage (Kandel, 2020). In the 2022 cropping season, the lowest nitrogen rate (60 kg ha^{-1}) resulted in higher SPAD values compared to the 2023 season (Table 14). This suggests that the 2022 season had more favourable conditions for chlorophyll development at lower nitrogen levels. In contrast, during the wet 2023 season, a high nitrogen application rate (100 kg ha^{-1}) led to an unexpected decrease in SPAD values compared to the lower nitrogen rate (Table 14). This decline may indicate that excessive moisture can cause nitrogen leaching, further diminishing nitrogen availability to crops, consequently SAPD values, as nitrogen is a basic component of chlorophyll content. A significant interaction between soil water content and nitrogen application rates has been previously reported in relation to SPAD values (Ma et al., 2023). These results highlight the complex interaction between nitrogen application rates, environmental conditions, and crop growth stages, further highlighting the need for precise nitrogen management practices to optimize durum wheat growth, particularly under varying seasonal conditions.

Table 9. The interaction effect analysis between durum wheat varieties and nitrogen levels concerning leaf reflectance traits measured at the various stage

	Tillering	Booting	Flowering
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N (kg ha ⁻¹)	GH	Varieties	LAI			NDVI			SPAD		
			LAI	NDVI	SPAD	LAI	NDVI	SPAD	LAI	NDVI	SPAD
60	Winter	GK Bétadur	5.23	0.68	49.59	6.04	0.77	54.43	4.32	0.79	53.67
		GK Julidur	4.48	0.73	52.38	6.01	0.79	56.39	4.16	0.80	55.91
		MV Hundur	4.52	0.69	50.96	5.98	0.77	57.66	4.85	0.81	56.30
		MV Pelsodur	3.59	0.66	51.41	5.41	0.74	58.48	3.93	0.77	56.47
		MV Pennedur	4.98	0.66	48.29	5.94	0.75	57.94	4.31	0.76	54.62
		MV Vékadur	4.37	0.69	51.46	6.15	0.75	58.39	4.61	0.78	57.93
	Spring	Durablank	2.90	0.73	60.88	2.49	0.51	49.12	2.75	0.77	53.89
		Duragolg	2.58	0.73	61.31	2.49	0.43	52.69	2.64	0.77	52.83
		Tamadur	2.17	0.71	56.51	2.02	0.31	42.22	2.83	0.77	51.26
100	Winter	GK Bétadur	5.17	0.63	48.83	7.73	0.72	54.04	4.42	0.81	53.38
		GK Julidur	5.29	0.69	51.86	6.93	0.78	57.62	4.41	0.84	55.90
		MV Hundur	5.13	0.67	50.58	7.19	0.77	55.34	4.73	0.83	56.86
		MV Pelsodur	4.43	0.67	56.03	6.40	0.76	57.71	4.67	0.82	57.03
		MV Pennedur	5.51	0.61	49.69	6.75	0.75	56.32	4.81	0.80	54.77
		MV Vékadur	5.17	0.70	54.15	6.95	0.72	57.55	5.23	0.81	56.04
	Spring	Durablank	3.42	0.74	60.89	2.41	0.45	50.09	3.19	0.80	54.15
		Duragolg	3.11	0.75	61.85	2.38	0.41	51.56	3.28	0.81	54.88
		Tamadur	3.24	0.75	56.74	2.18	0.39	47.45	3.23	0.79	52.77
LSD_{0.05}			0.52	0.07	2.49	0.91	0.04	2.46	0.81	0.03	2.46
CV (%)			11.3	6.70	5.20	18.00	5.90	3.70	11.90	0.70	4.90

NB: GH = Growth Habit of the tested varieties.

The significant improvement in SPAD values under both low and high nitrogen doses during the dry 2022 season suggests that moisture availability may play a more dominant role than nitrogen availability in determining chlorophyll content under drought conditions. This indicates that, even with varying nitrogen application rates, moisture remains a critical factor influencing plant health and chlorophyll content during periods of water stress. The consistent positive response to nitrogen application, regardless of the dosage, further implies that nitrogen was not a limiting factor during the drought year, indicating the importance of effective water management strategies in maximizing crop productivity in dryland environments. This variation may suggest that drought conditions in 2022 led to more efficient nitrogen utilization or altered nutrient dynamics, which could be linked to physiological adaptations of the plants under stress. These observations emphasize the critical role of water management in maximizing durum wheat productivity in dryland environments and suggest that further research into the interaction between moisture and nitrogen could lead to more targeted strategies for improving crop resilience under varying environmental conditions.

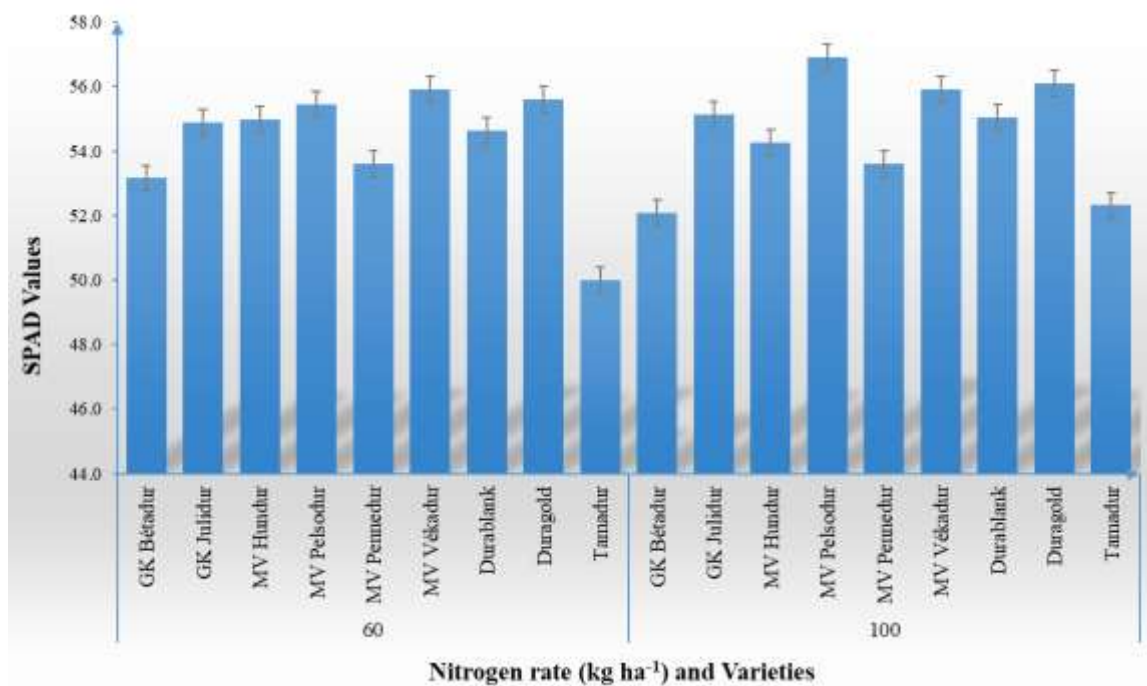


Figure 13. Interaction between durum wheat varieties and nitrogen application rates on average relative chlorophyll content across two cropping seasons, Debrecen-Látókép, 2022-2023 cropping season. Treatment means are statistically significant at $P=0.001$

The most significant interaction observed was between nitrogen rate and the tested durum wheat varieties. This interaction resulted in a significantly different ($p<0.05$) effect on SPAD values, with spring-sown varieties exhibiting a more pronounced positive response to higher nitrogen levels compared to the winter-sown varieties (Table 9; Figure 13). The contrasting response of winter-sown varieties to higher (100 kg ha^{-1}) nitrogen rate, where some varieties attained minimum values under increased nitrogen rate, suggests a complex interaction between nitrogen application and winter planting conditions. This could indicate that certain winter-sown durum wheat varieties are less responsive and even negatively affected by higher nitrogen levels, possibly due to factors such as varietal characteristics, environmental conditions, and agronomic practices.

While nitrogen application improved this particular trait, increasing nitrogen beyond 100 kg ha^{-1} did not yield further benefits and instead led to declines in SPAD values (Figure 13). The observed variability in response to nitrogen application among durum wheat varieties is largely influenced by genetic differences, environmental interactions, and agronomic practices. Varieties that exhibited increased SPAD values at higher nitrogen rates, such as MV Pelsodur across developmental stages, likely possess traits related to

efficient nitrogen uptake and utilization (Table 9). These traits may include enhanced NUE, where plants convert nitrogen into biomass and chlorophyll more effectively, resulting in improved vegetative growth and chlorophyll content, both of which are essential for maximizing yield potential (Gaju et al., 2011). These varieties may also exhibit more robust physiological mechanisms that enable them to optimize nitrogen assimilation, even under varying environmental conditions.

In contrast, varieties that demonstrated minimal or even negative growth responses to higher nitrogen inputs may have reached a physiological saturation point. In such cases, the plants' ability to uptake and assimilate nitrogen becomes constrained, leading to diminishing returns in terms of growth and productivity. This phenomenon may be associated to specific genetic traits that limit the plant's nitrogen uptake capacity or the efficiency with which excess nitrogen is metabolized. When nitrogen supply exceeds the plant's demand, physiological inefficiencies can arise, such as imbalances in nutrient uptake, nitrogen toxicity, or disruption in root-shoot signaling (Farhan et al., 2024). These responses highlight the need to recognize the limitations of nitrogen fertilization in varieties that are prone to nitrogen saturation, particularly in environments where additional nitrogen may cause stress rather than boost growth. Integrating nitrogen fertilization with biochar application enhances photosynthetic attributes by mitigating nitrogen toxicity and preventing nitrogen deficiency, as biochar's porous structure adsorbs excess nitrogen and gradually releases stored nitrogen, promoting sustained plant growth (Khan et al., 2021).

In the 2021 cropping season, notable varietal differences were observed among the tested durum wheat varieties, which had a statistically significant effect ($p < 0.05$) on relative chlorophyll content (Table 10). This result indicates that spring-sown durum wheat varieties possess varying capacities to respond to environmental factors such as nutrient availability and drought stress. Among the varieties studied, a marked difference was evident in the timing of leaf greening and yellowing, with SPAD values ranging from 49.0 to 52.3 for variety Colliodur and from 54.3 to 62.7 for Durablank (Table 10). Durablank consistently demonstrated higher SPAD values, suggesting a greater leaf chlorophyll content under drought conditions. The higher chlorophyll content in spring-sown varieties including Durablank may reflect a superior ability to manage water stress compared to other varieties, potentially attributed to genetic traits that enhance drought

resilience. A substantial genetic variability in leaf chlorophyll content among durum wheat varieties has been previously reported (Hamblin et al., 2014; Kizilgeci et al., 2021).

Table 10. Influence of genetic divergence in spring-sown durum wheat varieties on selected Morphophysiological traits across growth stages during 2021 cropping season

Varieties	Stem Elongation			Booting			Heading			Flowering			GY (kg ha ⁻¹)
	LAI	NDVI	SPAD	LAI	NDVI	SPAD	LAI	NDVI	SPAD	LAI	NDVI	SPAD	
Colliodur	2.0	0.81	49.0	2.3	0.81	49.0	3.9	0.71	56.8	3.4	0.68	52.3	6605
Durablank	1.3	0.78	54.3	2.8	0.85	56.6	3.9	0.77	65.3	3.8	0.73	62.7	6851
Duragold	1.3	0.79	53.6	2.8	0.82	55.0	3.7	0.74	65.9	3.5	0.72	61.6	7000
Tamadur	1.4	0.79	51.8	2.1	0.79	51.8	2.7	0.64	58.8	2.3	0.58	53.5	4953
LSD_{0.05}	0.11	0.015	1.19	0.13	0.019	1.03	0.16	0.016	1.36	0.17	0.027	1.9	238.27
CV (%)	10.9	1.50	3.4	8.0	1.9	2.9	6.5	1.8	3.3	7.8	3.2	5.0	3.0

Key to abbreviations: GY (kg ha⁻¹): Grain yield; LSD_{0.05}: Least Significant Difference; CV (%): Coefficient of Variation; NDVI: Normalized Difference Vegetation Index; SPAD: Soil Plant Analysis Development; LAI: Leaf Area Index

The substantial differences in SPAD readings between the varieties are likely due to inherent genetic variations that influence chlorophyll synthesis and retention under stress conditions. Durablank's higher SPAD values suggest it has a greater capacity to maintain chlorophyll content, which is essential for photosynthesis, especially during periods of water scarcity. This ability to sustain higher chlorophyll levels could be attributed to several genetic mechanisms, including enhanced regulation of stomatal conductance, improved activation of antioxidant pathways that protect chlorophyll from oxidative damage, and more efficient water use that mitigates the effects of drought stress. In contrast, the reduction in chlorophyll content observed in the variety Colliodur under drought conditions may be attributed to disruptions in chloroplast ultrastructure. Drought conditions can reduce photosynthetic efficiency, leading to an imbalance between light energy absorption and its utilization in the carbon assimilation process. This imbalance results in the overproduction of electrons, which in turn triggers the generation of reactive oxygen species (ROS) (Veres et al., 2019).

If the generation of reactive oxygen species (ROS) is not adequately neutralized by antioxidants in a timely manner, it can lead to further plant growth inhibition. This occurs through damage to the cell membranes, disruption of DNA and RNA enzyme functions,

and the induction of oxidative stress (Das et al., 2014). This disruption could not only impair photosynthetic efficiency but also reduces the activity of chloroplast pigment synthase, the enzyme responsible for synthesizing chlorophyll pigments. The availability of essential raw materials for chlorophyll synthesis diminishes, slowing down overall plant metabolism and resulting in lower chlorophyll content in the leaves (Li et al., 2024). These genetic traits likely contribute to Durablank's superior drought tolerance and its ability to sustain photosynthetic efficiency under stress conditions. On the other hand, the lower SPAD values observed in Colliodur may indicate a reduced capacity to maintain chlorophyll content under similar conditions, potentially making it more vulnerable to drought-related yield losses. This contrast highlights the importance of considering specific genetic traits when selecting durum wheat varieties for cultivation in drought-prone environments.

Table 11. Influence of varietal difference and foliar based nutrient supply on SPAD (chlorophyll content) values, grain yield and protein content of spring-sown varieties

Nutrients	Varieties	SPAD Values				GPC (%)	GY (kg ha ⁻¹)
		SE	BT	HS	FS		
Control	Colliodur	49.8	49.4	57.4	52.6	14.3	6932
	Durablank	53.4	55.8	65.6	62.1	15.3	6944
	Duragold	53.3	54.1	66.8	62.3	14.3	7054
	Tamadur	51.0	52.8	56.9	52.7	16.6	4802
Sulphur	Colliodur	47.9	47.7	56.4	52.1	16.5	6348
	Durablank	54.3	56.4	64.3	62.5	16.8	6891
	Duragold	55.0	55.3	65.9	61.1	16.4	6920
	Tamadur	52.5	51.2	59.4	54.9	16.3	5389
Zinc	Colliodur	49.2	50.0	56.6	52.1	16.4	6536
	Durablank	55.3	57.5	66.0	63.6	15.2	6717
	Duragold	52.7	55.6	65.0	61.4	15.1	7025
	Tamadur	52.0	51.6	60.1	52.9	15.7	4669
LSD _{0.05}		2.10	2.47	2.48	3.12	0.69	397
CV (%)		3.4	2.9	3.3	5.0	3.1	5.5

Key to abbreviations: **ST:** Stem elongation; **BT:** Booting; **HS;** Heading stage; **FS;** Flowering; **GPC (%):** Grain Protein content; **GY (kg ha⁻¹):** Grain yield; **SPAD:** Soil Plant Analysis Development

The maintenance of photosynthetic pigments, such as chlorophyll, has been proposed as a key indicator of drought tolerance in various crops (Monteoliva et al., 2021). The implications of these results for durum wheat breeding programs are significant. Agronomists and wheat breeders might prioritize chlorophyll content and drought resilience as key selection criteria, using SPAD readings as a practical tool for screening

varieties (Kettani et al., 2023). Additionally, understanding the genetic basis of these traits can inform targeted breeding strategies that combine high chlorophyll content with other desirable agronomic traits, such as yield stability and disease resistance.

However, despite the substantial genetic variability among the tested durum wheat varieties, all consistently surpassed the optimal SPAD threshold level of 41.8 for wheat (Ghosh et al., 2020). This threshold is generally associated with enhanced grain yield, especially under stress conditions. The fact that all varieties exceeded this threshold indicates that they were able to maintain chlorophyll levels above the optimal level, which is often linked to better photosynthetic performance and potential yield improvements under challenging growing conditions. Maintaining high leaf chlorophyll content enhances light interception and photosynthetic efficiency, both of which are critical for maximizing yield under drought conditions (Monteoliva et al., 2021). The ability to sustain higher chlorophyll levels during water stress indicates a valuable trait for improving drought tolerance. Additionally, it reduces oxidative stress, thereby contributing to better overall plant health and sustained yield under adverse conditions.

4.3.2. SPAD Values Dynamics as an Indicator of Durum Wheat Yield Under Drought Conditions

The relationship between grain yield and SPAD (relative chlorophyll content) in durum wheat is strongly positive, given that chlorophyll is central to photosynthesis, directly influencing grain development and overall yield (Table 13). In this study, relative chlorophyll content, measured using SPAD meters, was significantly ($p < 0.05$) affected by nitrogen management and environmental conditions. Varieties such as Duragold and Durablank, which exhibited higher chlorophyll levels, achieved notable yields of 7468 kg ha⁻¹ and 6901 kg ha⁻¹, respectively (Table 13). These results emphasize the utility of SPAD readings as a reliable, non-destructive indicator of crop productivity, as they reflect plant health and nutrient utilization efficiency under varying environmental conditions. Higher SPAD values, indicative of increased chlorophyll content, were consistently associated with high-yielding varieties, indicating the critical role of nitrogen in chlorophyll synthesis and, consequently, photosynthetic activity.

Nitrogen's contribution to chlorophyll synthesis ensures optimal light capture and carbon assimilation during critical growth stages, both of which are essential for maximizing biomass production and grain yield (Noor et al., 2023). This highlights the importance of

integrating chlorophyll monitoring into agronomic practices, particularly as part of nutrient management strategies aimed at sustaining yield under water stress conditions. The study further indicates the potential of chlorophyll content dynamics (CCD) as an indirect measure of drought resilience. Under water stress conditions, maintaining higher chlorophyll levels can signify a variety's ability to sustain photosynthetic efficiency despite limited water availability. The physiological basis for this lies in chlorophyll's role in optimizing light capture and energy transfer, which supports carbon fixation and plant growth even under suboptimal conditions. These results have practical implications for breeding programs, as selecting varieties with superior CCD can enhance drought tolerance and yield stability in durum wheat. Similarly, agronomic strategies that optimize nutrient availability, particularly nitrogen, can sustain chlorophyll levels and mitigate yield losses under water stress.

The observation that durum wheat varieties with higher SPAD values (relative leaf chlorophyll content) did not consistently achieve the highest grain yields, even under sufficient nitrogen availability, indicates the complexity of factors influencing durum wheat productivity (Table 10). While spring-sown varieties such as Duragold exhibited higher relative chlorophyll levels compared to Durablank, the latter ultimately outperformed Duragold in grain yield (Table 10). This highlights that the relationship between leaf chlorophyll concentration and grain yield is multifaceted, shaped by the genetic makeup of the variety and its interaction with environmental factors. Although increased chlorophyll content is generally associated with enhanced photosynthetic capacity and greater yield potential, other determinants such as stress tolerance, nutrient use efficiency, and overall plant health also play critical roles in shaping yield outcomes.

Durablank's superior yield performance, despite lower relative chlorophyll levels, suggests that its enhanced stress tolerance mechanisms may have been pivotal. These mechanisms could include more efficient water use or greater resistance to biotic and abiotic stresses, which are particularly critical under water-stress conditions. This result aligns with the study's broader implications, emphasizing that chlorophyll content dynamics (CCD) should not be viewed in isolation but rather as part of a complex physiological and genetic framework. These insights are particularly relevant for breeding programs aimed at improving durum wheat resilience, as well as for agronomic strategies designed to optimize yield under variable environmental conditions.

Durablank may also possess genetic traits that enable more efficient nutrient utilization, which could compensate for its lower chlorophyll content. Interestingly, increased grain yield in varieties with relatively low leaf chlorophyll content might be linked to reduced photochemical damage. Varieties with lower chlorophyll levels may absorb just enough light energy for optimal photosynthesis, thereby minimizing excess energy absorption that could lead to photochemical damage. This mechanism potentially enhances overall photosynthetic efficiency (Hamblin et al., 2014). Consequently, varieties with lower chlorophyll content may be better adapted to converting light energy into biomass, ultimately contributing to improved grain yield. The reduction in photochemical damage allows for more efficient use of absorbed light energy, bolstering the photosynthetic process and biomass production. Additionally, chloroplasts—rich in chlorophyll and vital for photosynthesis—are nutrient-dense organelles. In varieties with lower chlorophyll levels, nutrient allocation might be more efficient, particularly under nutrient-limited soil conditions (Hamblin et al., 2014). This suggests that nutrient-use efficiency could play a pivotal role in the superior performance of such varieties.

The observed correlation between SPAD measurements and grain yield further suggests the practical utility of SPAD meters for optimizing nitrogen management and refining varietal selection strategies. A comprehensive understanding of the interaction between chlorophyll content and nutrient efficiency is critical for managing nitrogen applications and selecting durum wheat varieties that perform well under diverse environmental conditions (Yasir et al., 2019). While SPAD readings offer valuable insights into nitrogen status and crop productivity, the relationship between chlorophyll content, nutrient allocation, and yield is inherently complex. The case of Durablank, which achieved high yields despite lower chlorophyll levels, illustrates that reduced chlorophyll content does not necessarily translate to diminished yield potential. This highlights the importance of considering both physiological and genetic traits when developing strategies for breeding and agronomic management of durum wheat under water stress conditions.

In water-limited environments, the relationship between leaf chlorophyll concentration and grain yield becomes more nuanced. While high chlorophyll content is generally linked to greater photosynthetic capacity, it does not always translate into higher yields under water stress conditions. This suggests the importance of considering additional physiological traits, such as drought tolerance, when selecting wheat varieties. A holistic approach to varietal selection is essential, accounting for a range of genetic and

environmental factors beyond chlorophyll content alone. Traits like root architecture, water use efficiency, and resilience to abiotic stresses are critical for developing durum wheat varieties capable of maintaining productivity under variable and challenging conditions. Integrating these traits into breeding programs can yield varieties that are not only high-performing but also adaptable to diverse and water-stressed environments. These efforts align with broader goals of agricultural sustainability and food security, ensuring consistent yields in the face of increasing climatic uncertainties.

The relative chlorophyll concentration in durum wheat leaves exhibited high sensitivity to nitrogen application and varietal differences, particularly under drought conditions. This sensitivity establishes chlorophyll content as a reliable early indicator of nitrogen deficiency, enabling timely interventions to mitigate potential yield losses. The use of chlorophyll meters to monitor nitrogen levels facilitates precise adjustments in nitrogen inputs based on crop requirements, thereby improving nitrogen use efficiency and enhancing both grain yield and protein content. This study further demonstrated that, across a range of durum wheat varieties and nutrient regimes, relatively uniform SPAD readings were strongly associated with improvements in both quantitative and qualitative traits. The positive relationship between grain yield, protein content, and early-season SPAD values aligns with findings from Singh and Ali (2020), emphasizing the utility of SPAD measurements in guiding nitrogen management.

Varieties with early-season SPAD readings exceeding 50 (unitless) consistently achieved higher grain yields and protein concentrations compared to those with lower readings (Table 10). This correlation was particularly pronounced under drought conditions, indicating the value of chlorophyll meters in assessing nitrogen status and identifying wheat varieties with superior stress tolerance (Yasir et al., 2019). Varieties that maintained higher SPAD readings under water-limited conditions exhibited enhanced drought tolerance and more stable yields, highlighting the critical role of SPAD-based monitoring in promoting resilient and productive durum wheat cultivation systems. Integrating SPAD measurements into agronomic practices, can optimize nitrogen application while supporting the sustainability of durum wheat production under diverse and challenging environmental conditions.

Aligning fertilization strategies with the crop's specific needs can ensure efficient nitrogen utilization, reducing waste and preventing excessive application (Ghosh et al.,

2020). In the context of climate change and environmental sustainability, determining optimal nitrogen levels through SPAD readings becomes increasingly important. This approach not only enhances crop productivity but also supports environmental conservation by minimizing nitrogen runoff. However, further research is needed to explore the sensitivity of SPAD readings across different developmental stages of durum wheat. These studies would help refine sensing strategies for site-specific and seasonal fertilizer applications, thereby improving nitrogen management and contributing to sustainable agricultural practices.

4.3.3. Temporal SPAD Trends and Their Association with Nitrogen Fertilization

Monitoring temporal variations in SPAD readings throughout the growing season is essential for effective nitrogen management in durum wheat. SPAD meters, which assess leaf chlorophyll content, offer a non-destructive and timely method to monitor nitrogen status, enabling precise adjustments to fertilization practices. Under drought conditions, nitrogen application significantly affected SPAD readings ($p < 0.05$), with noticeable variations across different growth stages, particularly during the 2021 cropping season (Table 12). When nitrogen was applied at a rate of 60 kg ha^{-1} , SPAD values were markedly higher than in the control treatment, illustrating that optimal nitrogen levels can enhance the photosynthetic efficiency of durum wheat (Table 12).

The SPAD readings ranged from 53.3 to 60.1, with the highest values occurring around the heading stage (Figure 14). This peak in SPAD values during the heading stage can serve as a practical benchmark for nitrogen application, indicating that further fertilization beyond this stage may offer limited benefits, particularly for farmers utilizing split application methods. Temporal variations in SPAD readings throughout the growing season are crucial for effective nitrogen management in durum wheat. SPAD meters, which assess leaf chlorophyll content, offer a non-destructive and timely method to monitor nitrogen status, enabling precise adjustments to fertilization practices. Under drought conditions, nitrogen application had a significant effect on SPAD readings ($p < 0.05$), with noticeable variations across different growth stages during the 2021 cropping season (Table 12, Figure 14).

Table 12. Variation in relative chlorophyll content, grain yield, and spike density (m²) and protein content influenced by variety × nitrogen interaction during different developmental stages (2021 cropping season).

N Rate (kg ha ⁻¹)	Varieties	SPAD Values				SPD (m ²)	GPC (%) (kg ha ⁻¹)	GY
		SE	BT	HS	FS			
Control	Colliodur	47.2	43.0	54.9	48.6	190.3	13.1	6509
	Durablank	53.8	52.8	64.7	61.3	211.2	15.8	6800
	Duragold	53.3	51.7	64.9	59.8	200.2	15.4	6531
	Tamadur	49.8	47.3	56.0	50.1	137.9	15.2	4014
60	Colliodur	50.7	55.0	58.7	55.9	241.9	16.2	6702
	Durablank	54.9	60.4	65.8	64.2	220.8	17.4	6901
	Duragold	54.0	58.3	66.9	63.3	212.7	17.3	7468
	Tamadur	53.8	56.4	61.6	56.9	170.3	15.3	5893
LSD_{0.05}		2.34	1.36	3.69	2.99	14.52	0.72	958
CV (%)		3.40	2.90	3.30	5.00	7.70	2.80	3.0

When nitrogen was applied at a rate of 60 kg ha⁻¹, the SPAD values were markedly higher than in the control treatment, illustrating that optimal nitrogen levels can enhance the photosynthetic efficiency of durum wheat. The SPAD readings ranged from 53.3 to 60.1, with the highest values occurring around the flowering (Figure 14). This peak in SPAD values during the heading stage can serve as a practical benchmark for nitrogen application, indicating that further fertilization beyond this stage may offer limited benefits, particularly for farmers utilizing split application methods. These offer valuable insights into the relationship between nitrogen application and SPAD readings, providing clear guidance for optimizing fertilization strategies. Aligning nitrogen inputs with the crop's physiological needs can avoid over-application, which is especially important in drought-prone conditions where maximizing nitrogen use efficiency is crucial. This not only supports yield stability but also minimizes environmental impacts, making nitrogen management more sustainable in challenging growing environments.

These results are pivotal for refining nitrogen application strategies in drought conditions, as they enable efficient use of resources while sustaining crop productivity. The strong correlation between nitrogen levels and SPAD readings, which reflect leaf chlorophyll content, highlights the potential of chlorophyll meters to predict durum wheat growth and yield, especially in the face of climate change. As climate change introduces fluctuations in temperature, precipitation, and other environmental variables that influence crop growth and nutrient absorption, tools like chlorophyll meters become increasingly

valuable. They provide a non-destructive, real-time approach to assessing plant health and nutrient status, enabling farmers to make timely adjustments to management practices. This real-time data allows for more precise nitrogen applications, ensuring the crop's needs are met under varying environmental conditions, thus promoting resilience and optimizing yield.

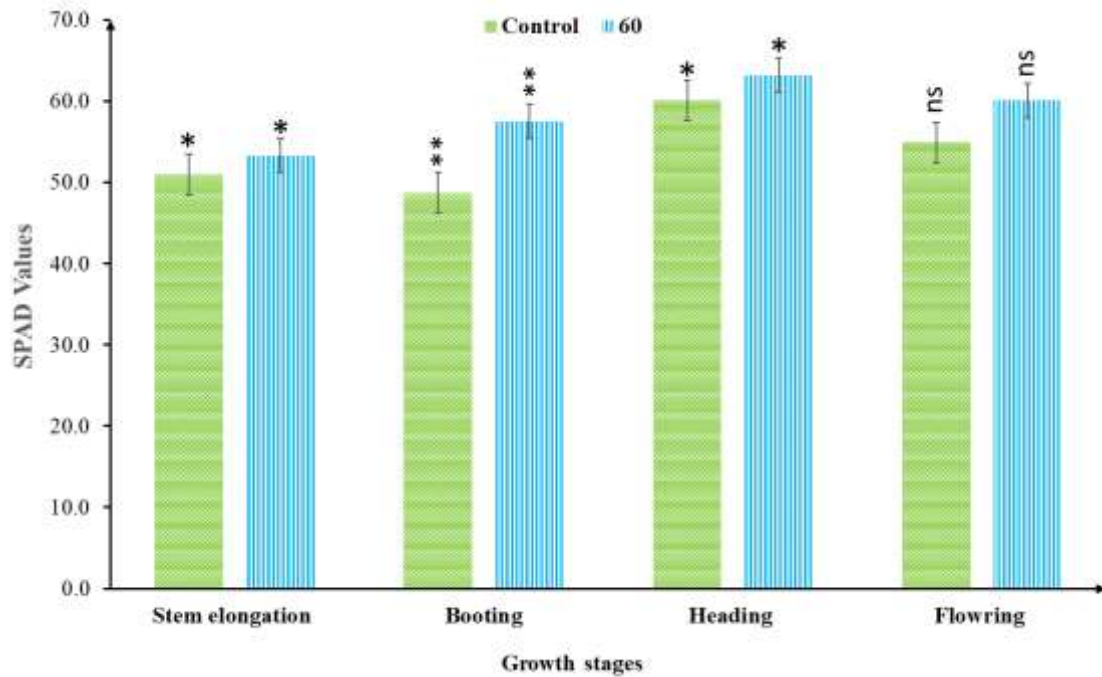


Figure 14. Illustrates the dynamics of SPAD readings (relative chlorophyll content) across different developmental stages in the absence and presence of nitrogen (60 kg ha^{-1}) fertilization under drought conditions, Debrecen-Látókép, 2021 cropping season. Bars indicated as “ns”, is statistically no significant, **single asterisk** (*) is significant at 0.05% and bars with a **double asterisks** (**) are statistically significant at 0.01%.

The results further indicating that zinc and sulphur-containing fertilizers did not significantly affect relative chlorophyll content or leaf nitrogen status under drought conditions ($p < 0.05$) suggest that these nutrients, when applied alone, may not be adequate to optimize durum wheat performance in water-limited environments (Table 13). Although relative chlorophyll content decreases at later stages, applying zinc and sulphur fertilizers late in the season to boost this trait may not be agronomically or economically beneficial. Therefore, we recommend that zinc and sulphur fertilizers be applied during the early growth stages to effectively support chlorophyll content and optimize nutrient uptake during key periods of crop development.

Table 13. Influence of varietal difference and foliar based nutrient supply on SPAD (relative chlorophyll content) values, grain yield and protein content of spring-sown varieties

Nutrients	Varieties	SPAD Values				GPC (%)	GY (kg ha ⁻¹)
		SE	BT	HS	FS		
Control	Colliodur	49.8	49.4	57.4	52.6	14.3	6932
	Durablank	53.4	55.8	65.6	62.1	15.3	6944
	Duragold	53.3	54.1	66.8	62.3	14.3	7054
	Tamadur	51.0	52.8	56.9	52.7	16.6	4802
Sulphur	Colliodur	47.9	47.7	56.4	52.1	16.5	6348
	Durablank	54.3	56.4	64.3	62.5	16.8	6891
	Duragold	55.0	55.3	65.9	61.1	16.4	6920
	Tamadur	52.5	51.2	59.4	54.9	16.3	5389
Zinc	Colliodur	49.2	50.0	56.6	52.1	16.4	6536
	Durablank	55.3	57.5	66.0	63.6	15.2	6717
	Duragold	52.7	55.6	65.0	61.4	15.1	7025
	Tamadur	52.0	51.6	60.1	52.9	15.7	4669
LSD _{0.05}		2.10	2.47	2.48	3.12	0.69	397
CV (%)		3.4	2.9	3.3	5.0	3.1	5.5

Key to abbreviations: **ST:** Stem elongation; **BT:** Booting; **HS:** Heading stage; **FS:** Flowering; **GPC (%):** Grain Protein content; **GY (kg ha⁻¹):** Grain yield; **SPAD:** Soil Plant Analysis Development

The lack of response to zinc and sulphur in this context suggests the complexity of nutrient-stress interactions and highlights the limitations of relying solely on micronutrients to mitigate drought stress. This indicates that zinc and sulphur fertilization, while beneficial for certain physiological processes such as enzyme activation (zinc) and amino acid synthesis (sulphur), may not address the broader physiological demands posed by drought stress, such as water retention, osmotic regulation, and overall plant vigour. As drought impacts nutrient mobility and uptake, zinc and sulphur might not be effectively transported to the plant tissues where they are most needed. This aligns with earlier studies suggesting that micronutrient uptake and efficiency are often constrained under drought due to reduced root activity and compromised soil moisture conditions (Kapoor et al., 2020).

While zinc and sulphur are essential, their standalone application may not provide significant agronomic or economic benefits in terms of improving relative chlorophyll content at the later developmental stage. Hence, more comprehensive strategies are required to enhance durum wheat performance under drought conditions. Integrating drought-tolerant varieties, which possess intrinsic genetic traits such as deeper root

systems or more efficient water use, can provide a more robust response to water-limited conditions. Varieties that inherently maintain higher chlorophyll levels under drought stress would naturally exhibit better photosynthetic efficiency, thus contributing to sustained productivity. Foliar sprays during periods of active growth or before critical developmental stages, such as tillering or grain filling, can enhance nutrient uptake by bypassing soil-mediated constraints. This approach could allow for the direct absorption of nutrients through the leaves, potentially mitigating the negative effects of drought on root uptake.

Early-season application of zinc and sulphur, when nutrient demand is high and plant metabolic activity is vigorous, might also contribute to better nutrient utilization and boost overall plant health. Early-season nutrient interventions are crucial for maximizing the efficiency of nutrient uptake under suboptimal growing conditions (Kumari et al., 2022). Additionally, combining zinc and sulphur applications with other macro and micronutrients, or incorporating them into broader fertilization programs, may enhance their effectiveness. Nitrogen plays a pivotal role in chlorophyll synthesis and may synergize with zinc and sulphur to improve nutrient absorption and photosynthesis. Balanced nutrient programs that address the multifaceted demands of plants, particularly under stress conditions, would likely be more beneficial than relying on individual nutrient applications.

4.3.4. Harnessing NDVI for Enhanced Durum Wheat Productivity and Nutrient Optimization

The analysis showing that nitrogen application at variable rates significantly ($p < 0.05$) influenced NDVI profile across the cropping years highlights the critical role nitrogen plays in shaping vegetative growth dynamics, as captured by remote sensing tools such as NDVI (Table 14). However, the observed decrease in NDVI values at higher nitrogen rates, especially during the 2023 cropping season, is an interesting finding, particularly given that NDVI is typically used as a proxy for plant biomass and health. While NDVI is typically expected to rise with increased nitrogen availability due to enhanced biomass production, the results suggest that in certain conditions, particularly with high nitrogen inputs, NDVI may fail to accurately reflect plant health and biomass. This result highlights the limitations of using NDVI as a growth indicator in dense durum wheat canopies, particularly under high nitrogen and wet conditions.

Table 14. The interaction effects of nitrogen rate and growing season on physio-morphological traits at various growth stages, and lodging occurrence

N (kg ha ⁻¹)	Years	Tillering			Booting			Flowering			LDG (%)
		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	0.0
	2023	2.57	0.60	51.21	3.29	0.60	49.10	3.70	0.77	54.12	80.7
100	2022	6.40	0.81	55.79	7.13	0.71	58.98	4.82	0.84	56.50	0.0
	2023	2.60	0.57	53.24	3.74	0.57	49.40	3.62	0.78	53.68	90.1
LSD _{0.05}		1.21	0.08	0.94	0.65	0.03	2.49	0.94	0.03	1.14	1.9
CV (%)		23.1	9.2	7.70	24.0	8.30	5.20	20.0	3.80	6.60	9.2

NDVI's sensitivity to plant biomass diminishes when LAI values exceed a critical threshold, typically between 2.5 and 3 (Rhezali et al., 2017). This could be due to the rapid changes in vegetation reflectance and the fact that their canopy reflectance is primarily influenced by complex multiple scattering interactions within the leaf layers (Qiao et al., 2024). When LAI surpasses this threshold, the canopy becomes so dense that NDVI values saturate, making it difficult to distinguish subtle differences in biomass and plant health. This phenomenon, known as NDVI saturation, limits the usefulness of this index for monitoring nitrogen dynamics in dense, high-biomass crops, particularly during the later growth stages when LAI is at its peak. NDVI saturation can mask signs of nitrogen deficiency, reducing its effectiveness as a tool for real-time nitrogen management in dense cropping systems (Naicker et al., 2024).

In the case of durum wheat, this implies that in nitrogen-rich environments, especially during wet seasons, the crop might experience excessive vegetative growth without corresponding increases in yield or quality. This phenomenon might also be exacerbated by the tendency for plants to allocate excess nitrogen toward shoot growth at the expense of reproductive development, particularly under non-limiting moisture conditions. Such a response could explain the lower NDVI values recorded, as the additional biomass contributes to canopy density, but without the associated increases in plant health or productivity that NDVI typically captures. Moreover, the saturation of NDVI under dense canopies has broader implications for remote sensing applications in agriculture. As LAI increases, NDVI becomes less reliable in distinguishing between different nitrogen levels or plant health conditions. This is especially critical in precision agriculture, where

accurate assessments of crop nutrient status are necessary to inform variable rate nitrogen applications.

These limitations could be overcome by integrating other remote sensing tools or indices that complement NDVI, such as the Green Chlorophyll Index (GCI) or Soil Adjusted Vegetation Index (SAVI), which may offer more sensitivity in high-biomass, nitrogen-rich environments (Vidican et al., 2023). These additional tools, when used in conjunction with NDVI, can provide a more holistic picture of crop growth and nutrient status, particularly under conditions where NDVI's sensitivity is limited due to canopy saturation. Furthermore, the implications of this nitrogen-induced NDVI saturation must be considered in the context of climate change, where increasing variability in rainfall patterns might further complicate nitrogen management strategies. In wetter years, excessive nitrogen application could lead not only to reduced NUE but also to environmental concerns like nitrate leaching or greenhouse gas emissions, especially in soils already saturated with nitrogen. Therefore, integrating remote sensing with agronomic models that account for nitrogen dynamics under varying moisture conditions could be essential for optimizing nitrogen applications in a more climate-resilient manner. This could improve both productivity and environmental sustainability, aligning with broader agronomic goals of reducing excess nitrogen use and minimizing its environmental impact, such as leaching and greenhouse gas emissions.

The contrasting effects of nitrogen application rates on NDVI values across the 2022 and 2023 cropping seasons indicates the significant interaction between agronomic practices and climatic conditions. In the drought-affected 2022 season, the application of 100 kg ha⁻¹ of nitrogen led to the highest NDVI readings, indicating that the enhanced nutrient availability allowed durum wheat to exhibit healthier, more vigorous vegetation despite water scarcity. This result is consistent with prior research that highlights the importance of nitrogen in promoting crop resilience during stressful conditions. However, the subsequent 2023 season, characterized by excessive soil moisture, resulted in diminished NDVI values at both nitrogen rates (60 and 100 kg ha⁻¹) (Table 14).

The drought conditions in 2022 and the saturated soil in 2023 demonstrate that while nitrogen application can positively influence crop health, it cannot fully mitigate the adverse effects of unfavourable climatic conditions. This emphasizes that climatic factors can overshadow the benefits of nutrient management, leading to suboptimal crop health

and productivity. The observed interactions between nitrogen application rates and growing seasons highlight the necessity for seasonal-specific nitrogen management strategies. A universal approach to nitrogen fertilization may not be effective; instead, adjustments based on prevailing weather patterns, such as rainfall and temperature, are essential for maximizing crop health and yield. Such adjustments could involve varying nitrogen application rates according to forecasted weather conditions to better align with the crop's physiological needs.

The pronounced variability in NDVI values, particularly concerning crop varietal differences, further complicates nitrogen management strategies. The significant interaction ($p < 0.05$) between nitrogen application rates and varietal responses indicates that spring-sown varieties exhibit a more favourable response to higher nitrogen levels (100 kg ha^{-1}) compared to winter-sown varieties (Table 9). This results aligns with previous studies suggesting that different sowing dates can influence nutrient uptake efficiency and overall plant response to nitrogen. The muted response of winter-sown varieties under increased nitrogen levels raises important questions about their adaptability to varying nutrient conditions. Factors such as root structure, nitrogen uptake efficiency, and specific stress responses may contribute to the observed differences. For instance, winter-sown varieties might possess genetic traits that render them less responsive to additional nitrogen, potentially due to their growth strategy, which emphasizes resilience in cooler, wetter conditions. This could hinder their ability to effectively utilize high nitrogen inputs, leading to suboptimal growth

Although nitrogen application improved NDVI values, increasing the rate beyond 100 kg ha^{-1} did not yield significant additional benefits and even led to a decline in NDVI. This decline could be attributed to nitrogen saturation in the soil or increased susceptibility to nitrogen-related stress factors. In contrast, during the dry growing season of 2022, significant ($p < 0.05$) improvements in NDVI were observed with both nitrogen application rates. This suggests that, under water stress conditions, nitrogen availability might be less critical for growth parameters, as even the lower application rate of 60 kg ha^{-1} was adequate to meet durum wheat's needs. The results further indicate that there is an optimal nitrogen level beyond which additional nitrogen may not provide benefits and could potentially harm the crop, possibly due to nutrient imbalances or environmental stresses. It appears that spring-sown varieties may benefit from higher nitrogen levels, whereas winter-sown varieties might require more conservative applications to avoid

negative impacts. Additionally, in dry seasons, nitrogen application rates should be optimized to lower levels, as moisture availability becomes the primary limiting factor as far as NDVI is considered as a trait.

The durum wheat varieties \times nitrogen application rates \times developmental stages interaction was found to significantly impact NDVI values (Table 9). However, the genetic response of the tested varieties to the applied nitrogen was inconsistent across different developmental stages in improving NDVI profile during the season. At the tillering and booting stage MV Pennedur's NDVI values increased with higher nitrogen rates, highlighting that the impact of nitrogen on NDVI is stage-specific and varies with the growth dynamics at different developmental phases. In contrast, during the tillering stage, MV Pennedur exhibited lower NDVI values at lower nitrogen rates but higher NDVI values at increased nitrogen levels (Table 9). The observed decrease in NDVI values at lower nitrogen rates indicates limited vegetative growth, while higher nitrogen rates enhance NDVI, reflecting improved canopy development and photosynthetic efficiency. This variability in NDVI responses suggests that different durum wheat varieties have distinct sensitivities and adaptations to nitrogen fertilization. Additionally, this result indicates that the impact of nitrogen on NDVI is stage-specific and that MV Pennedur benefits from increased nitrogen availability at specific developmental phases.

The variability in response to nitrogen application levels can be attributed to genetic differences among the varieties, interactions with environmental factors, and agronomic practices. Varieties that showed an increase in NDVI values with higher nitrogen rates probably possess traits enabling them to efficiently utilize nitrogen, resulting in enhanced vegetative growth and chlorophyll content. Variety GK Julidur exhibited increased NDVI values at higher nitrogen rates during the booting stage, indicating its ability to effectively assimilate nitrogen during this growth phase (Table 9). On the other hand, varieties that displayed minimum NDVI values under higher nitrogen rates may have reached a point of nitrogen saturation, encountering physiological limitations in nitrogen assimilation. This saturation can lead to reduced nitrogen use efficiency and potential stress responses. Genetic predispositions to nitrogen use efficiency, root architecture, and tolerance to nitrogen-induced stress also contribute to the observed differences in response among varieties. varieties with a more extensive root system may better access and utilize available nitrogen, improving their NDVI values under higher nitrogen rates.

Wheat grain yield is indeed a complex trait influenced by a multitude of phenotypic characteristics and their genetic foundations. The relationship between NDVI and grain yield indicates the importance of monitoring plant health and growth conditions throughout the growing season. Panek, and Gozdowski (2020) indicates that each 0.1-unit increase in NDVI throughout the growing season can correlate with an increase in grain yield ranging from 1.1 to 2.6 tons per hectare. This substantial correlation emphasizes the value of NDVI as a diagnostic tool for informing agronomic practices aimed at improving yield under increasingly variable climatic conditions. The observed increase in NDVI values due to early-season nitrogen fertilization further illustrates the vital role of nutrient management. When nitrogen is applied adequately at the beginning of the growing season, it stimulates robust vegetative growth, leading to higher NDVI readings that signify healthier and denser plant canopies. This vigorous early growth is crucial for maximizing light interception and overall photosynthetic efficiency, both of which are essential for achieving optimal grain yield. However, as the growing season progresses, the dynamics of nitrogen redistribution come into play.

Nitrogen is often reallocated from older leaves to support the development of younger, actively growing tissues. This redistribution can lead to the discoloration of older leaves, which subsequently results in diminished NDVI values later in the season due to the loss of chlorophyll content and reduced photosynthetic capacity in those leaves. Therefore, while early-season nitrogen applications are critical for enhancing NDVI and promoting plant health, it is equally important to monitor nitrogen availability and distribution throughout the growing season to ensure sustained crop performance. In general, strategic nitrogen management—particularly focusing on timely and adequate early-season applications—can substantially enhance NDVI and LAI values, thereby supporting vigorous vegetative growth and maximizing grain yield potential. Aligning nitrogen management practices with the physiological needs of the wheat crop throughout its growth stages, particularly under drought conditions, can better navigate the challenges posed by climate variability and enhance overall productivity.

4.3.5. Optimizing Durum Wheat Fertilization with Canopy Reflectance Sensors

Nitrogen application has been shown to effectively induce variability in the Leaf Area Index during the six fully expanded leaf stage, which is a crucial period for assessing plant health and growth in durum wheat. LAI serves as a vital biophysical trait, providing

insights into the physiological status and overall vigour of the plants. The interaction effects among nitrogen application, varietal differences, and foliar nutrient applications were statistically significant ($p < 0.05$), indicating that nitrogen plays a crucial role in influencing the physiological and structural characteristics of different durum wheat varieties, as evidenced by the observed changes in LAI measurements (Table 12). In the 2021 cropping season, co-fertilizing with foliar-based sulphur-containing nutrients alongside a soil-based nitrogen application of 60 kg ha^{-1} led to notable increases in LAI.

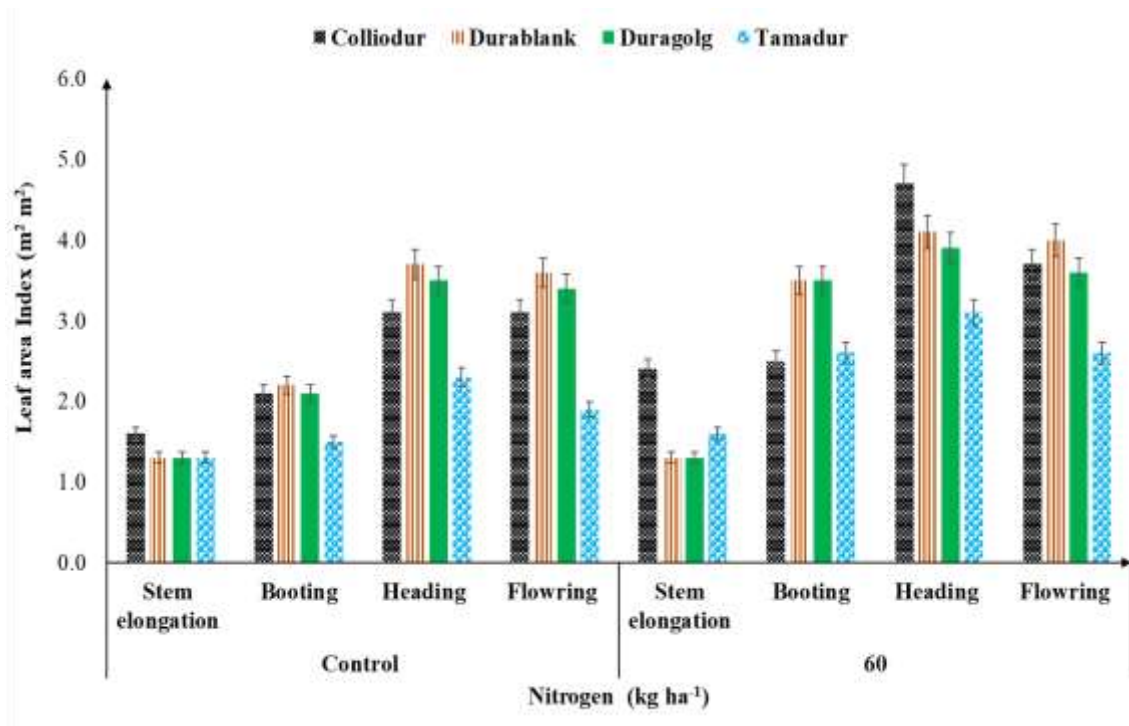


Figure 15. Interaction effects of nitrogen application and varietal differences on leaf area index during progression of developmental stages, Debrecen-Látókép, 2021 cropping season. Treatment means are statistically significant at $P=0.05$

However, the extent of this effect varied across different durum wheat varieties (Table 11 and 12; Figure 15). This variability indicates that certain durum wheat varieties are more sensitive or responsive to the combined fertilizer treatment than others. This highlights the importance of considering varietal differences when implementing nutrient management strategies. The responsiveness of LAI to nitrogen and foliar nutrient applications suggests that specific durum wheat varieties may benefit more from adjusted fertilization approaches, potentially leading to improved growth and productivity. This variability also emphasizes the necessity for agronomists and farmers to adopt flexible nitrogen management practices that account for the unique characteristics and needs of different wheat varieties.

The varietal dependence of the response to nitrogen application suggests that even small adjustments in nitrogen levels can significantly impact LAI, directly influencing plant growth and vigour in a stage-dependent manner. Numerous studies corroborate these findings, indicating that nitrogen fertilizers consistently improve LAI in wheat crops (Zhang et al., 2021; Kizilgeci et al., 2021). The varietal sensitivity highlights the need for adjusted nitrogen fertilization approach in durum wheat, as different varieties exhibit unique nutrient uptake efficiencies and photosynthetic capacities. This results further emphasize the need to consider varietal characteristics and genotype-specific responses when developing nitrogen management strategies for durum wheat production systems (Table 9). The specific nutrient uptake efficiency and photosynthetic capacity of different varieties should be integrated into management practices to maximize the benefits of nitrogen application. It is crucial for agronomists and other stakeholders to take into account the specific growth stages of the crops when applying these nutrients.

The LAI was identified as a biophysical trait highly sensitive to changes in developmental stages and nutrient application (Figure 15). The combined analysis of variance revealed similar trends for LAI, with values initially increasing and subsequently declining as the crop progressed through its developmental stages. The maximum recorded LAI value was observed for variety Colliodur at approximately heading stage but plateaued thereafter, even under a nitrogen application rate of 60 kg ha⁻¹ (Figure 15). This result highlights the dynamic nature of LAI in durum wheat, which varies significantly between the vegetative growth phase and the maturity or senescence phases. During the early stages, all leaves are typically green, contributing to a higher LAI. However, as the plant matures, the canopy increasingly includes a mixture of yellowing, senescing, and dead leaves, which reduces LAI measurements.

Timing the application of nitrogen and other fertilizers at critical developmental stages can significantly enhance their effectiveness on LAI and overall crop productivity. Through aligning nutrient management strategies with varietal needs and growth stages, producers can achieve better crop performance and, ultimately, higher yields in durum wheat cultivation. The LAI measurements varied in response to developmental plasticity and fertilizer applications (Table 13). Among the tested varieties, Durablank exhibited a higher LAI when treated with sulphur fertilizer compared to the other varieties. This suggests that different varieties of the same species may respond differently to applied inputs, highlighting the importance of selecting appropriate varieties coupled with

specific nutrient management practices, particularly in stress-prone environments. It can be generally inferred that the positive correlation between LAI and developmental phases offers a promising avenue for improving grain yield in durum wheat. The impact of genetic variability on LAI was significant across various developmental stages, with varietal differences playing a key role in LAI expression (Table 15).

Table 15. The main effects of nitrogen application, nutrient supplementation (i.e. zinc and sulphur), varietal distinctions, and variations in cropping seasons on leaf area index at various growth stage.

Treatments		Tillering	Booting	Flowering	
N Rate (kg ha ⁻¹)	60	2.70	2.60	2.30	
	100	3.20	3.30	2.30	
	LSD _{0.05}	1.10	0.32	0.18	
	CV (%)	7.30	7.0	4.00	
Nutrients	Control	3.00	2.90	2.30	
	Zinc	3.10	2.90	2.30	
	Sulphur	2.90	2.90	2.40	
	LSD _{0.05}	0.19	0.17	0.14	
	CV (%)	10.5	3.20	2.20	
Varieties	Winter	GK Bétadur	4.37	5.20	6.88
		GK Julidur	4.28	4.88	6.47
		MV Hundur	4.79	4.83	6.58
		MV Pennedur	4.56	5.25	6.34
		MV Vékadur	4.92	4.77	6.55
		MV Pelsodur	4.30	4.01	5.91
	Spring	Durablank	2.97	3.16	2.45
		Duragold	2.96	2.84	2.43
		Tamadur	3.03	2.70	2.10
LSD _{0.05}		0.32	0.31	0.62	
CV (%)		4.70	11.30	4.60	

Winter-sown varieties, such as GK Bétadur, GK Julidur, and MV Vékadur, exhibited a progressive increase in LAI throughout the growing season, peaking at 6.88, 6.58, and 6.55, respectively, during the flowering stage (Table 15). In contrast, spring-sown varieties, including Durablank, Duragold, and Tamadur, displayed a decline in LAI as the season progressed. This suggests a potential limitation in their ability to sustain canopy development under the environmental conditions of the growing season (Table 15). The decline in LAI during later stages can be attributed to the transition from fully green leaves in the early season to a mix of green, yellow, and senescent leaves as the crop approaches maturity, thereby reducing overall LAI values. Conversely, the improvement in LAI prior to the heading stage is associated with the expansion of the photosynthetic

leaf area, which enhances carbohydrate production (Din et al., 2017). This increase in photosynthetic capacity during vegetative growth contributes to greater leaf dry weight and biomass accumulation, suggesting the critical role of early-season LAI in determining crop health and yield potential.

4.4. Nutrient Management Practices for Enhancing Productivity, Nutritional Compositions, and Quality in Durum Wheat

4.4.1. 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 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 (Table 16). 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. 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.

The yielding potential of genetic material significantly influences grain protein content in durum wheat. When assessing the allometric relationships of grain quality traits relative to biological potential, it was observed that varieties with higher grain protein content typically exhibited lower yield potential, while high-yielding varieties tended to accumulate lower grain protein content, likely due to the dilution effect (Table 2; Figure 16). The maximum grain protein content was recorded in the variety GK Julidur, which achieved 16.55% protein when sulphur was combined with a high nitrogen rate, and 16.36% when zinc was combined with a high nitrogen rate (Table 16). 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 sulphur and 13.97% with zinc combined with a high nitrogen rate, despite its high-yielding potential (Table 15). This pattern highlights the trade-off between grain yield and protein content, as high-yielding varieties often produce lower

protein content, whereas varieties with maximum protein content are generally low-yielding. This trade-off may occur if the primary genes responsible for improving grain quality traits are closely linked to, or intensely correlated with, genes that have a detrimental effect on yield potential (Melash and Ábrahám, 2022).

Table 16. 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

This trade-off further highlights the need for breeding and nutrient management strategies that carefully balance the optimization of grain yield with the enhancement of protein content. Addressing this challenge is critical, as grain protein content directly influences pasta quality and market value, making it essential for the economic sustainability of durum wheat production. An intermediate set of varieties, characterized by higher grain protein content and gluten strength, warrants further research to fully explore their genetic variability and potential for improving grain quality traits (Giunta et al., 2020). These varieties represent a valuable source of genetic diversity, essential for identifying durum wheat varieties best suited for producing high-quality pasta, bread, and other bakery products (Mefleh et al., 2019). High-yielding varieties including MV Pelsodur may require additional interventions or adjustments in nutrient management to improve protein content without compromising their yield potential. On the other hand, varieties with inherently high protein content might benefit from strategies aimed at enhancing their grain yield.

It can be universally inferred that a one-size-fits-all approach to nutrient application is unlikely to be effective in optimizing durum wheat production. Instead, adjusted nutrient management strategies that take into account varietal differences and the synergistic effects of multiple nutrients are essential for enhancing grain protein content. Indeed, understanding these dynamics is crucial for developing durum wheat varieties that can balance high yield and nutritional quality, ensuring adaptability to diverse environmental conditions and meeting market demands. This approach could lead to durum wheat varieties that not only thrive under various environmental conditions but also meet the quality standards required for pasta, bread, and other bakery products.

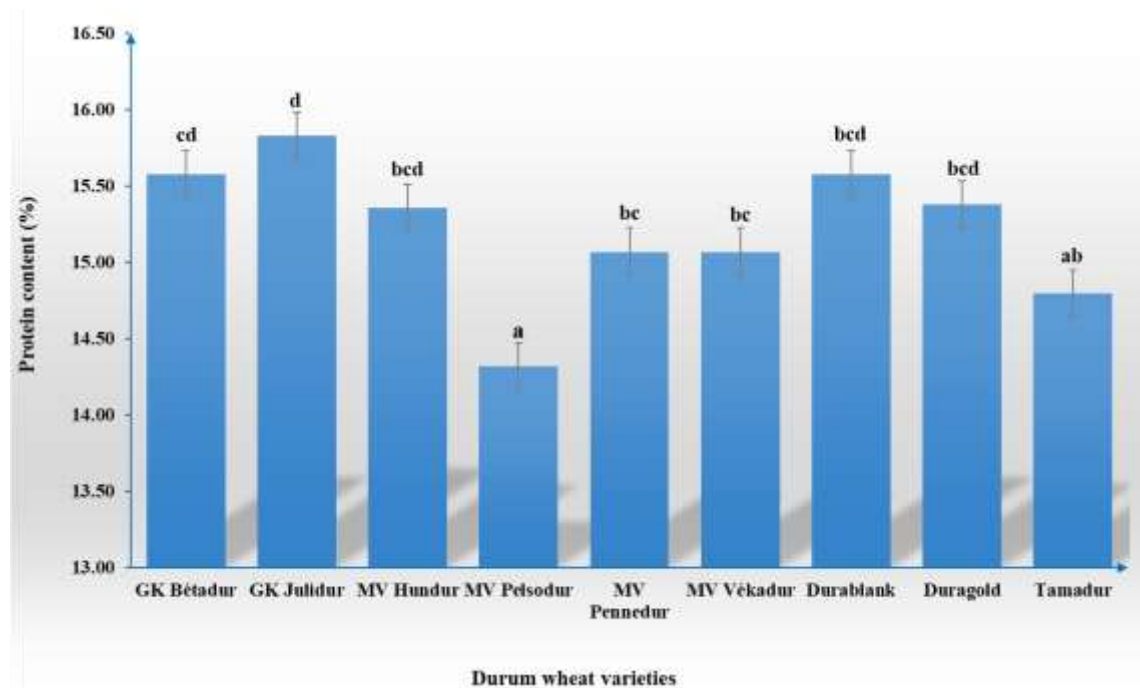


Figure 16. The main effect of genetic variation among durum wheat varieties on grain protein content, Debrecen-Látókép, 2022-2023 cropping season. Bars with the same letters are not statistically significant, whereas bars with different letters are statistically significant at $p < 0.01$.

When durum wheat varieties were evaluated across different cropping seasons, it was found that the formation of grain protein content significantly influenced by the interaction between genetic variability and seasonal growing conditions. In the 2023 cropping season, the highest grain protein content was recorded in MV Hundur (16.04%), Duragold (15.95%), and Durablank (15.91%). In contrast, during the 2022 cropping season, the highest protein content was observed in GK Julidur (15.92%), GK Bétadur (15.55%), and Durablank (15.24%) (Figure 16). This variability highlights how different varieties respond to changing environmental conditions across growing seasons. The fact

that top-performing varieties in one season may not perform similarly in another highlights the complex interaction between genetic and environmental factors in determining grain protein content. This seasonal variation emphasizes the need to consider both varietal characteristics and environmental conditions when aiming to optimize grain protein content in durum wheat production.

Although the grain protein content was higher during the 2023 cropping season, the variation in grain protein content among the tested varieties was more pronounced in the 2022 cropping season, with a 13.39% variation among the tested varieties, compared to a 7.22% variation in the 2023 season (Figure 16). This disparity highlights the complex interaction between environmental conditions and genetic factors in determining grain protein content. In 2022, the drier conditions likely intensified the expression of genetic differences, as varieties adapted to stress conditions exhibited greater variability in protein content. The higher protein content in 2023, despite the lower variability among varieties, suggests that environmental factors, such as moisture availability, played a significant role in leveling the playing field for durum wheat growth and development. This indicates that when environmental factors such as water availability and nutrient supply are optimal, the differences in genetic traits may have less impact on the final grain protein content, resulting in relatively uniform expression of protein-related traits across varieties. In such conditions, the environment assumes a more dominant role in determining grain quality, often overshadowing genetic differences. However, in the 2022 season, which experienced drier conditions, the differences among the varieties became more evident, suggesting that stress factors can enhance the manifestation of genetic variability.

The comparative analysis further reveals that grain protein content was significantly ($p < 0.05$) influenced by the main effects of both the growing season and genetic landscape (Figure 16 and 17). These analysis indicates substantial variability in grain protein content attributable to genetic differences among the tested varieties, with the maximum observed difference in protein content between the two growing seasons being 5.40%, while the variation between the varieties reached up to 10.54% (Figure 16, Table 7). This suggests that genetic differences among the varieties exert a greater influence on grain protein content than environmental factors such as interannual climatic variation. The significant variation observed among varieties further highlights the crucial role of genetic factors in protein synthesis and accumulation, indicating that breeding efforts could more

effectively enhance grain protein content by focusing on genetic traits rather than solely adjusting agronomic practices or environmental conditions. Hence, understanding these dynamics is essential for developing durum wheat varieties that meet both yield and nutritional quality targets, ensuring better adaptability to varying environmental conditions and market demands.

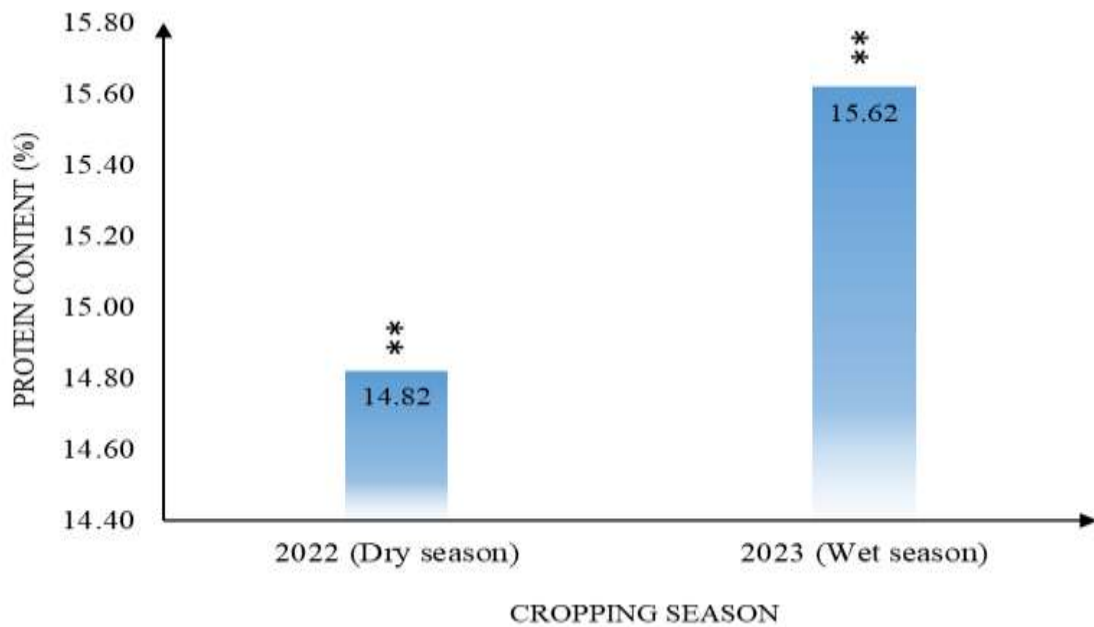


Figure 17. Variation in grain protein content due to differences in cropping season, Debrecen-Látókép, 2022-2023 cropping season. Bars marked with two asterisks (**) indicate a statistically significant difference at the $P < 0.001$ level of probability.

The other important factor that significantly ($p < 0.05$) determines grain protein content was found to be variation in growing season. Differences in growing seasons can substantially influence the environmental conditions, such as temperature, precipitation, and soil moisture, all of which play critical roles in the physiological processes of durum wheat development. In the 2023 cropping season, characterized by higher rainfall and more favourable conditions, the maximum grain protein content reached 15.62%, which was significantly higher than the 14.82% recorded during the drier 2022 cropping season (Figure 17). This notable difference suggests that the wetter conditions of the 2023 season facilitated better protein development in durum wheat. The relationship between water availability and protein synthesis in durum wheat is suggested by the increased grain protein content observed in the 2023 season. Adequate moisture not only supports nutrient uptake but also enhances the metabolic processes essential for protein synthesis. In wet conditions, plants are better positioned to utilize available nitrogen effectively,

leading to higher protein concentrations in the grain. This is consistent with findings from studies that indicate water availability directly influences nitrogen uptake and utilization, ultimately affecting protein content in cereal crops (Din et al., 2017).

The interaction between genetic variability and environmental factors clearly emphasizes the importance of considering both elements in breeding programs and agronomic practices (Figure 18). It is crucial to select and develop durum wheat varieties that can maintain high protein content not only under ideal conditions but also in stressful environments, such as drought or nutrient deficiency. Agronomic and breeding programs should focus on enhancing traits that allow varieties to maintain high grain protein content even in adverse environments. This approach could improve the overall quality of durum wheat, ensuring its suitability for pasta and other products that require specific protein levels.

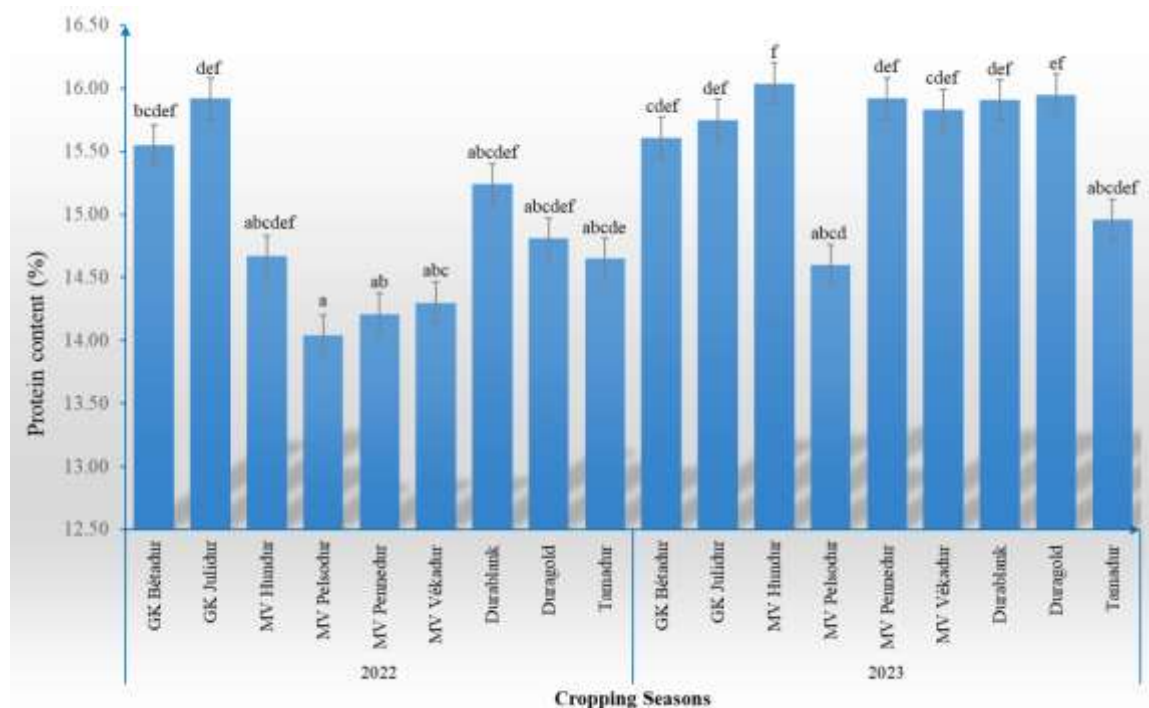


Figure 18. The interactive effect of crop genetic variation and differences in cropping season on grain protein content, Debrecen-Látókép, 2022-2023 cropping season. Bars with different letters indicate statistical significance at the 0.05 level of probability, while bars with the same letters indicate a statistically non-significant effect on grain protein content.

In general, the quality of durum wheat is shaped by the dynamic interaction between genetic potential and nutrient management. Varietal differences in yielding ability were observed, indicating that high-yielding varieties can achieve higher grain protein content

when nutrient application is adequate. Nitrogen fertilization contributed more to the variation in grain protein content than genotype under drought stress conditions. This indicates that while low-yielding varieties may produce higher grain protein in the absence of fertilization, high-yielding varieties significantly benefit from sufficient nitrogen supply to optimize protein content. A positive correlation was observed between leaf chlorophyll content and grain protein content, with chlorophyll levels ranging from 55 to 65.8 contributing to a 10.13% increase in protein content. Maintaining a grain protein content of around 13% is crucial for enhancing pasta quality, and this target was achieved in our study (14.3–16.8%) through the application of zinc, sulphur, and nitrogen fertilization, despite the influence of genetic factors on grain protein content. Durum wheat with higher protein content (<12%) results in pasta with improved elasticity, cooking tolerance, reduced stickiness, and better water absorption, thus enhancing overall quality (Melash et al., 2023).

4.4.2. The Influence of Nutrient Supply, Varietal, and Interannual Differences on Nutritional Composition and Concentration

The results of the chemical composition and nutritional value analyses of durum wheat varieties varied and were primarily dependent on their genetic properties. This genetic variability plays a crucial role in determining grain biochemical traits, influencing factors such as protein content and mineral composition. The data from the present study revealed significant ($p < 0.05$) differences in mineral concentrations between spring and winter wheat varieties (Table 17). Spring-sown varieties, such as Durablank and Duragold, accumulated higher concentrations of essential elements, including Zn, S, Mg, Al, Ca, Cu, Mn, and P, compared to their winter-sown counterparts. This trend aligns with findings from previous studies, which report that higher scaling exponents in spring wheat relative to winter wheat suggest greater relative accumulation of macronutrients other than nitrogen and phosphorus in spring wheat (Weih et al., 2021). These results underscore the importance of seasonal and varietal factors in determining the mineral composition of durum wheat, with spring wheat showing a clear advantage in the accumulation of nutrients. This difference suggests that genetic factors, as well as the specific growth patterns of spring-sown varieties, play a significant role in nutrient uptake and accumulation.

Spring-sown varieties may have a distinct advantage in accumulating certain nutrients due to their growth cycle, which could allow them to better capitalize on nutrient

availability during critical stages of development. Elements such as Zn, S, and P are essential for various physiological processes, including enzyme function, protein synthesis, and energy transfer, all of which contribute to grain quality. The accumulation of these nutrients in the spring-sown varieties indicates their potential to produce nutritionally superior grains, particularly in environments where nutrient management is a key focus. In contrast, the winter-sown varieties may have longer growing periods that subject them to different environmental conditions, potentially influencing nutrient uptake patterns. While winter-sown varieties may benefit from early moisture and cooler conditions, the spring-sown varieties' faster growth and nutrient assimilation might be more responsive to specific agronomic interventions, such as foliar nutrient applications.

The interaction effect between the tested durum wheat varieties and nitrogen application rates was statistically significant ($p < 0.01$) for grain elemental compositions, indicating that both genetic factors and nitrogen availability play crucial roles in determining nutrient accumulation in the grains (Table 18). Various nutrients, including Al, B, Ba, Cr, Fe, K, Mg, Mo, Na, and P exhibited significant variations due to the genotype-by-nitrogen interaction. The highest concentrations of these nutrients were generally observed at elevated nitrogen application rates, highlighting the importance of nitrogen in enhancing the nutritional quality of durum wheat grains. Higher nitrogen levels often facilitate better nutrient uptake and assimilation, resulting in increased concentrations of essential minerals. Nitrogen plays a pivotal role in metabolic processes, impacting the transport and incorporation of nutrients into grain tissues, thus influencing their elemental compositions. In many crops, increased nitrogen availability often correlates with improved nutrient content due to enhanced metabolic processes that facilitate nutrient uptake and utilization (Farhan et al., 2024).

While many nutrients showed an increase under high nitrogen application, S content in the grains displayed a unique trend. The maximum sulphur content was observed at lower nitrogen application rates, suggesting a complex interaction where low nitrogen conditions might favour the mobilization and accumulation of sulphur. This may be attributed to the reduced competition for uptake between nitrogen and sulphur at lower nitrogen levels, allowing for more efficient assimilation of sulphur into the grain. The role of sulphur in protein synthesis and enzyme function is well established, and its availability is crucial for optimizing the overall quality of wheat (Roa et al., 2024). On the other hand, nutrients such as Ca, Cu, Mn and Sr did not show significant responses to

the genotype-by-nitrogen interaction. This lack of significant influence may indicate that these particular nutrients are less sensitive to changes in nitrogen application rates or may be influenced more by soil characteristics and plant physiology rather than the specific interactions between genotype and nitrogen levels.

The interaction effect between growing years and nitrogen rates was found to be significant ($p < 0.01$) for grain elemental composition, emphasizing the intricate relationships between environmental conditions and nutrient management in durum wheat cultivation (Table 19). In contrast to the 2022 cropping year, which experienced drier conditions, the wet season in 2023 provided a more conducive environment for nutrient absorption. This relationship reveals how varying climatic conditions across different growing seasons can influence the effectiveness of nitrogen applications on nutrient uptake and grain quality. In the 2023 cropping year, characterized by wetter conditions, the maximum concentrations of several grain nutrients were observed (Table 19). This enhanced elemental composition can be attributed to improved nitrogen availability and overall nutrient mobility within the soil due to higher moisture levels. This relationship suggests that the wetter conditions not only facilitated better nutrient absorption but also improved the efficiency of nutrient utilization within the plants.

The observation that maximum grain sulphur content was recorded under a lower nitrogen application rate during the 2023 cropping year indicates a unique interaction between nitrogen and sulphur dynamics in durum wheat. This result reveals the complex relationship between these two essential nutrients and has important implications for nutrient management strategies aimed at optimizing grain quality. Nitrogen and sulphur are both vital nutrients for crops productivity and quality. While nitrogen is primarily associated with vegetative growth and protein synthesis, sulphur plays a key role in the formation of amino acids, proteins, and enzymes (Roa et al., 2024). Achieving a balance between these nutrients is crucial for optimal crop performance and quality. In many cases, the addition of sulphur to nitrogen fertilization enhances both yield and micronutrient content, though the incremental benefits diminish at higher nitrogen application rates (Klikocka, and Marks, 2018). This suggests that at higher nitrogen levels, crops prioritize nitrogen assimilation, potentially at the expense of sulphur metabolism. This competitive interaction highlights a critical consideration in nutrient management practices, especially where excessive nitrogen application is common in efforts to maximize yield.

Nitrogen and sulphur are both vital macronutrients for plant growth. While nitrogen is primarily associated with vegetative growth and protein synthesis, sulphur plays a key role in the formation of amino acids, proteins, and enzymes. Achieving a balance between these nutrients is crucial for optimal crop performance and quality. In many cases, excessive nitrogen application can lead to competitive inhibition of sulphur uptake, resulting in lower sulphur concentrations in the grain. When nitrogen levels are high, plants often prioritize nitrogen assimilation, which can detract from sulphur metabolism. This competitive dynamic is particularly relevant in nutrient management practices, where nitrogen is frequently applied in excess to maximize yield. The observation of higher sulphur content under lower nitrogen rates may suggest a stress response in durum wheat. When nitrogen availability is limited, plants might enhance their sulphur uptake to sustain vital metabolic processes and optimize protein synthesis. Under such conditions, plants often adapt their nutrient uptake strategies to balance their requirements, potentially increasing sulphur assimilation when nitrogen is scarce. This dynamic has significant implications for grain quality. Higher sulphur concentrations can improve the nutritional value of durum wheat, making it more suitable for pasta and bread production, where high-quality protein is essential. The unique interaction between nitrogen and sulphur emphasizes the need for integrated nutrient management strategies that account for the relationships between these two nutrients.

Table 17. The main effect nitrogen application rate, varietal difference, foliar application of nutrients and seasonal variability on nutritional composition of durum wheat grain.

Treatments		Grain Nutritional Composition (mg kg ⁻¹)															
		Al	B	Ba	Ca	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	P	S	Sr	Zn
Varieties	Durablank	8.25	1.12	2.40	319.64	0.23	5.32	41.61	4034.25	1101.07	37.24	0.30	19.82	3207.64	1608.61	1.50	34.70
	Duragold	8.77	1.02	2.07	279.87	0.21	5.11	42.11	4138.69	1117.72	37.30	0.32	18.30	3173.31	1662.97	1.29	31.05
	GK Bétadur	8.57	1.23	2.69	288.98	0.52	4.67	41.37	4218.86	987.14	32.86	0.34	19.15	2906.64	1424.78	1.83	24.14
	GK Julidur	8.24	1.18	2.83	301.42	0.41	4.79	39.11	4217.22	1005.98	33.78	0.33	19.10	2985.67	1582.33	1.68	23.75
	MV Pelsodur	7.68	1.07	2.98	278.31	0.34	4.47	36.48	4066.75	933.84	35.31	0.28	20.46	2931.00	1455.39	1.52	22.99
	LSD _{0.05}	0.51	0.30	0.17	16.87	0.07	0.24	1.82	136.48	54.15	1.80	0.02	1.57	169.31	28.05	0.08	1.35
	CV (%)	9.10	6.50	9.60	8.60	8.90	7.20	6.80	4.90	7.90	7.60	10.30	12.10	8.30	2.70	7.70	7.40
Fertility	Control	7.10	0.95	1.94	250.68	0.35	4.24	33.30	3587.45	887.81	32.01	0.29	16.32	2943.18	1527.97	1.60	26.99
	Sulphur	9.04	1.24	2.94	314.20	0.32	5.19	44.14	4398.58	1110.59	37.00	0.34	20.67	3059.72	1565.50	1.54	26.71
	Zinc	8.76	1.18	2.90	316.05	0.34	5.19	42.97	4419.43	1089.06	36.89	0.30	21.11	3119.65	1546.98	1.55	28.28
	LSD _{0.05}	0.34	0.10	0.29	27.44	0.05	0.30	1.56	158.12	55.06	1.55	0.02	1.30	150.18	25.43	0.07	1.30
	CV (%)	3.10	6.50	9.60	8.60	8.90	7.20	6.80	4.90	7.90	7.60	10.30	12.10	8.30	2.70	7.70	7.40
N Rate	60 kg ha ⁻¹	7.34	1.20	2.34	276.93	0.34	5.13	37.72	3891.56	996.05	34.77	0.35	20.61	2996.66	1641.61	1.83	28.33
	100 kg ha ⁻¹	9.26	1.05	2.85	310.35	0.35	4.61	42.55	4378.76	1062.25	35.82	0.28	18.12	3085.04	1452.02	1.29	26.32
	LSD _{0.05}	0.34	0.20	0.13	22.09	0.11	0.53	1.13	278.09	87.67	0.34	0.02	1.60	201.52	99.11	0.05	2.59
	CV (%)	3.50	5.00	4.20	2.50	8.70	3.10	0.80	1.90	2.40	0.30	1.50	2.30	1.90	1.80	0.90	2.70
Year	2022	6.64	0.89	1.62	247.23	0.14	5.14	34.53	3734.52	810.29	31.37	0.32	20.95	2557.30	1302.88	1.17	28.47
	2023	9.97	1.35	3.57	340.05	0.53	4.60	45.74	4535.79	1248.01	39.23	0.30	17.78	3524.40	1790.76	1.96	26.18
	LSD _{0.05}	0.30	0.10	0.10	10.79	0.04	0.15	1.06	76.59	33.22	1.12	0.01	0.94	113.07	29.57	0.04	0.93
	CV (%)	3.10	6.50	4.20	2.50	10.60	4.60	2.90	2.90	4.00	3.30	5.70	5.00	3.70	1.20	3.30	3.60

Table 18. Nutritional composition of durum wheat grain as influenced by the interaction effect between nitrogen rate and varietal difference

N (kg ha ⁻¹)	Varieties	Grain Nutritional Composition (mg kg ⁻¹)														
		Al	B	Ba	Ca	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	P	S	Sr
60	Durablank	7.19	1.14	2.10	306.12	0.20	5.62	37.74	3716.83	1028.33	35.87	0.33	19.57	2928.22	1709.56	1.76
	Duragold	8.50	1.01	1.95	257.34	0.20	5.32	39.52	3846.22	1097.84	37.59	0.35	16.83	2984.72	1763.83	1.55
	GK Bétadur	7.23	1.55	2.34	276.59	0.60	4.89	39.32	4109.44	965.57	32.80	0.39	22.55	3048.72	1520.78	2.08
	GK Julidur	7.10	1.29	2.54	281.71	0.40	5.18	37.15	3991.22	935.15	32.58	0.37	21.90	3042.50	1665.94	1.96
	MV Pelsodur	6.70	1.00	2.78	262.90	0.30	4.66	34.88	3794.06	953.36	35.04	0.30	22.19	2979.11	1547.94	1.83
100	Durablank	9.31	1.10	2.69	333.16	0.26	5.02	45.49	4351.67	1173.81	38.61	0.27	20.07	3487.06	1507.67	1.25
	Duragold	9.03	1.03	2.18	302.40	0.22	4.91	44.70	4431.17	1137.61	37.01	0.29	19.76	3361.89	1562.11	1.02
	GK Bétadur	9.91	0.90	3.05	301.36	0.44	4.46	43.43	4328.28	1008.70	32.93	0.29	15.75	2764.56	1328.78	1.59
	GK Julidur	9.38	1.06	3.13	321.12	0.41	4.39	41.06	4443.22	1076.81	34.98	0.29	16.31	2928.83	1498.72	1.40
	MV Pelsodur	8.67	1.14	3.19	293.72	0.38	4.28	38.08	4339.44	914.32	35.58	0.26	18.72	2882.89	1362.83	1.20
LSD _{0.05}		0.85	0.26	0.22	24.03	0.10	0.42	2.36	231.25	82.38	2.28	0.03	2.13	235.98	74.75	0.10
CV (%)		9.10	6.50	9.60	8.60	8.90	7.20	6.80	4.90	7.90	7.60	10.30	12.10	8.30	2.70	7.70

Table 19. Interaction effect nitrogen and growing season on nutritional composition of durum wheat grains

N (kg ha ⁻¹)	Year	Grain Nutritional Composition (mg kg ⁻¹)														
		Al	B	Ba	Ca	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	P	S	Sr
60	2022	5.98	1.01	1.56	247.73	0.13	5.60	33.48	3654.40	768.17	31.13	0.35	20.45	2628.73	1286.71	1.16
	2023	8.71	1.39	1.69	246.73	0.54	4.66	41.96	4128.71	1223.93	38.42	0.35	20.77	3364.58	1996.51	2.51
100	2022	7.30	0.78	3.13	306.13	0.15	4.68	35.59	3814.64	852.41	31.61	0.30	21.46	2485.87	1319.04	1.18
	2023	11.22	1.31	4.01	373.98	0.53	4.54	49.51	4942.87	1272.09	40.03	0.26	14.79	3684.22	1585.00	1.40
LSD _{0.05}		0.78	0.15	0.12	17.00	0.08	0.41	1.20	217.09	65.90	1.13	0.02	1.30	161.10	76.26	0.05
CV (%)		12.30	8.30	12.70	12.30	9.90	10.30	8.80	6.20	10.80	10.60	11.30	16.30	12.50	6.40	9.30

4.4.3. Genetic and Environmental Influences on Grain Zinc Concentration: Implications for Biofortification Strategies in Durum Wheat

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) (Figure 19). The variability in grain zinc concentration between the tested varieties was 50.87%, indicating the strong genetic component in zinc accumulation in durum wheat. This highlights the importance of selecting zinc-efficient varieties, such as Durablank, for improving zinc content in grain across different environmental conditions.

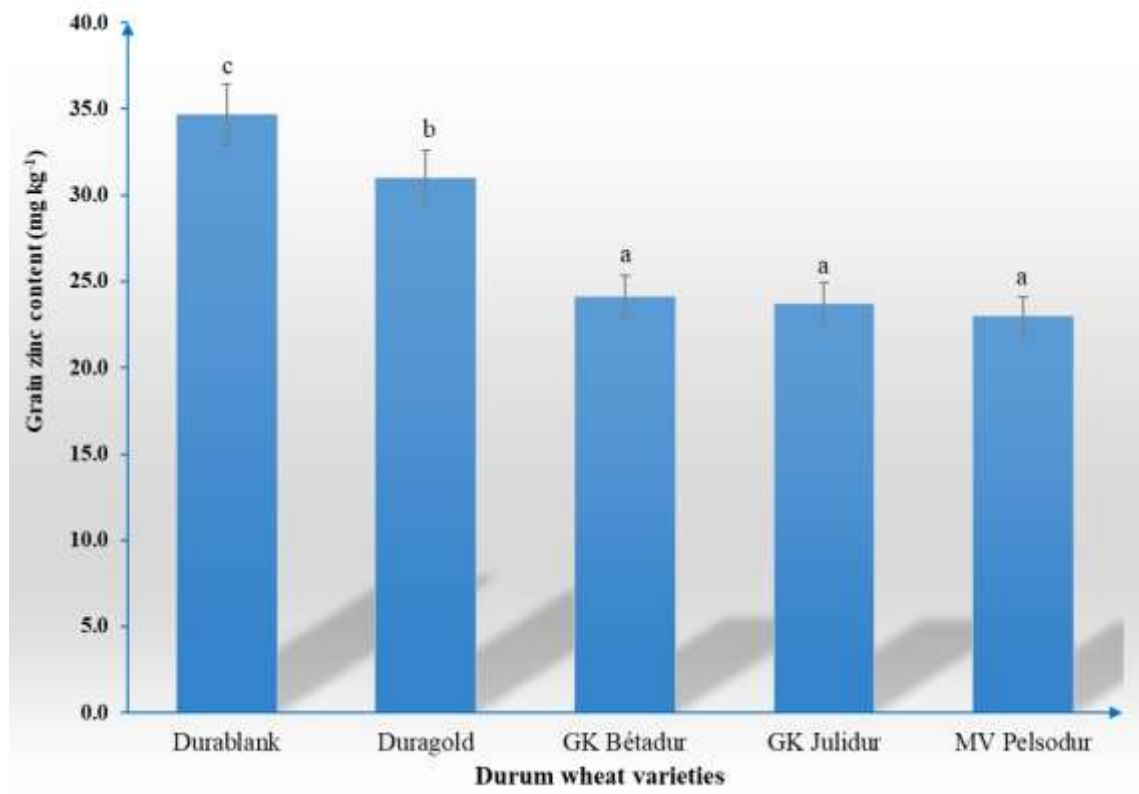


Figure 19. Influence of genetic variation among selected durum wheat varieties on grain zinc concentration, Debrecen-Látókép, 2022-2023 cropping season. Bars labeled with different letters indicate statistically significant differences at the 5% probability level.

The interaction between cropping years and durum wheat varieties was also found to significantly affect grain zinc concentration (Figure 20). 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. In the wet cropping season of 2023, Durablank continued to outperform other varieties in terms of grain zinc accumulation, recording a maximum concentration of 33.61 mg kg⁻¹ (Figure 20). This indicates that spring-sown durum wheat varieties, such as Durablank, are more effective at accumulating grain zinc compared to high-yielding, winter-sown varieties including MV Pelsodur and GK Julidur. The varieties accumulated more zinc in the grain during the dry season compared to the wet season. The variation in grain zinc concentration between the varieties was 45.31% during the dry season and increased to 58.99% during the wet season, demonstrating a greater disparity in zinc accumulation under different environmental conditions. These means that environmental factors, particularly water availability, significantly influence the ability of different 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.

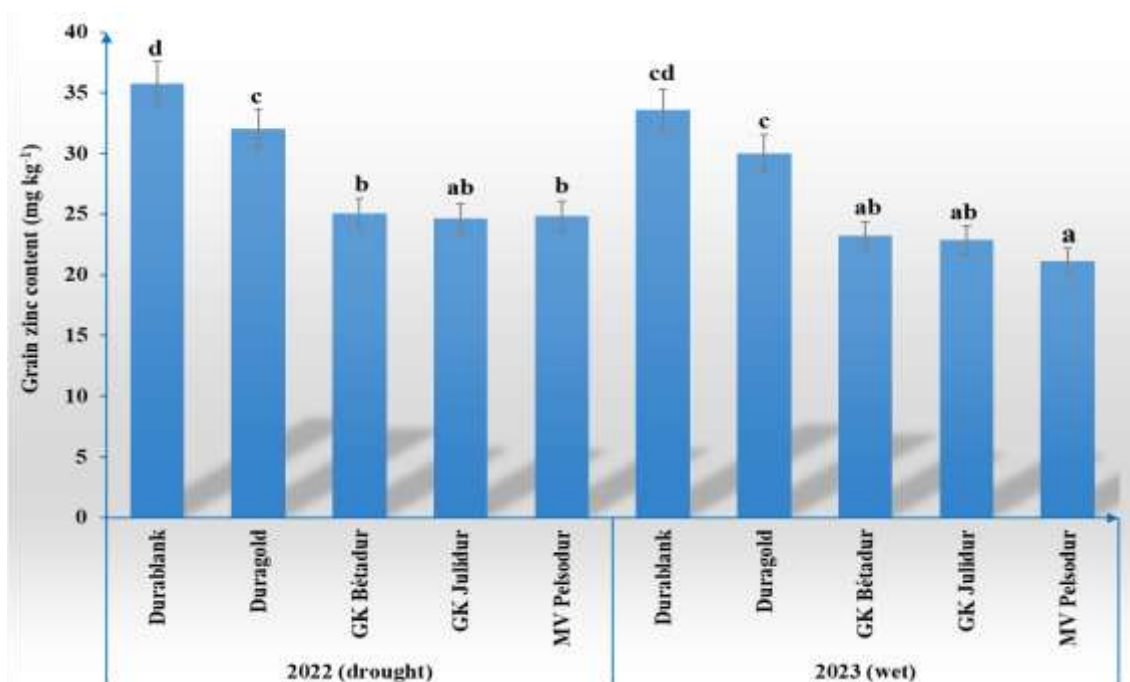


Figure 20. Interaction effect of durum wheat varieties and cropping seasons on grain zinc concentration, Debrecen-Látókép, 2022-2023 cropping season. Bars labeled with different letters indicate statistically significant differences at the 5% probability level.

A significant interaction effect was observed between foliar application of zinc, sulfur, and the tested durum wheat varieties (Figure 21). 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 21). This suggests a strong varietal ability to uptake and translocate zinc into the grain under foliar zinc application. In contrast, the high-yielding variety Pelsodur demonstrated the lowest grain zinc concentration, even when subjected to the same zinc and sulfur fertilization regime. These findings indicate that while Pelsodur is capable of producing higher grain yields, it is less efficient at accumulating zinc in the grain compared to Durablank under similar agronomic conditions.

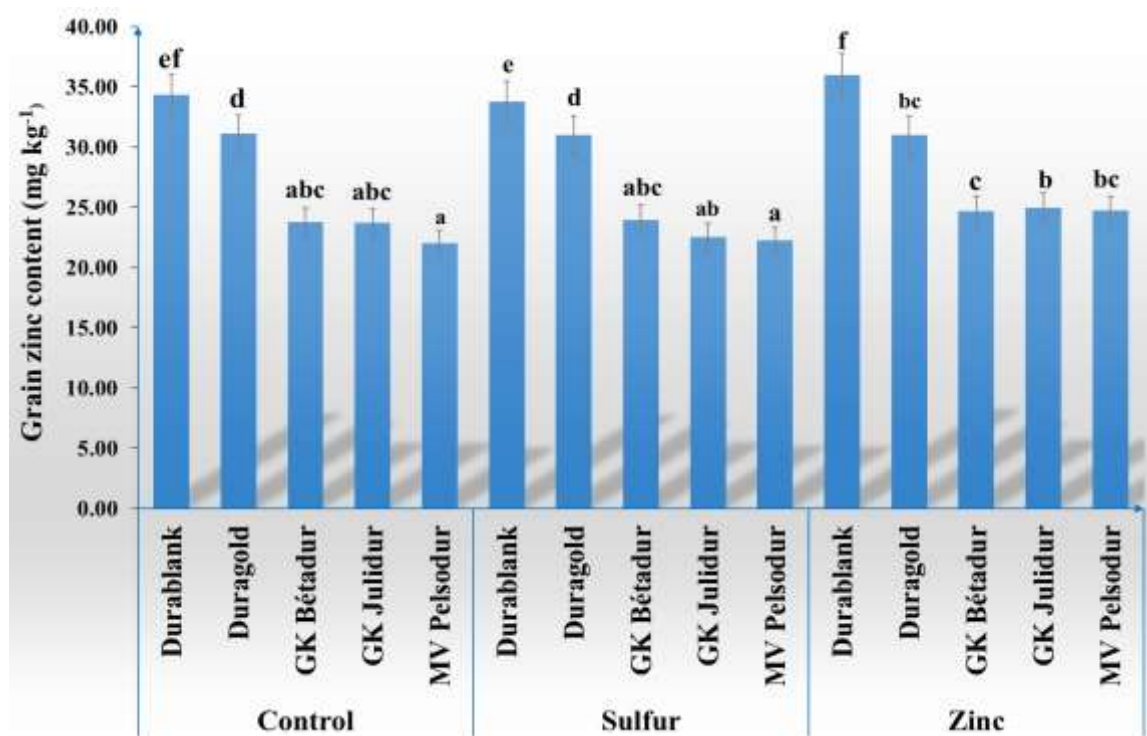


Figure 21. Impact of genetic diversity among durum wheat varieties on agronomic biofortification, Debrecen-Látókép, 2022-2023 cropping season. Bars labeled with different letters indicate statistically significant differences at the 5% probability level.

The results emphasize the critical role of genetic and environmental factors in determining grain zinc concentration in durum wheat, shedding light on the potential for zinc biofortification through targeted breeding strategies. The significant variability in grain zinc content among the tested varieties indicates the influence of genetic selection on micronutrient accumulation, with variety Durablank consistently exhibiting the highest zinc levels. This implies the potential of breeding zinc-efficient varieties as a viable strategy to combat zinc deficiency in human diets. The genetic variation of 50.87%

in zinc concentration among the tested varieties reinforces the importance of leveraging genetic diversity to enhance the nutritional profile of durum wheat. The fact that Durablank outperformed other varieties, including high-yielding ones such as MV Pelsodur and GK Julidur, suggests the potential of genetic selection for improving grain zinc concentration without sacrificing yield. This observation challenges the often perceived trade-off between nutrient density and crop yield, as demonstrated by Durablank's ability to maintain high zinc levels while still performing competitively in terms of grain productivity. A genetic variation in grain zinc concentration and the significant role that breeding for micronutrient efficiency can play in enhancing the nutritional quality of cereal crops has been previously highlighted (Tabbita et al., 2017).

The environmental component, particularly the influence of growing conditions such as water availability, further complicates zinc biofortification efforts. Interestingly, 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. A similar result has been previously reported, showing that grain zinc concentration during the dry season was approximately 50% higher than in the wet season (Shoormij et al., 2022; Rakotondramanana et al., 2024). The increase in zinc concentration during drier conditions suggests that limited water availability may enhance nutrient concentration in the grain, potentially due to reduced biomass or stress-induced mechanisms that improve nutrient uptake efficiency. Water stress can increase nutrient concentrations in crops by reducing biomass production, which may enhance the nutritional composition of grains.

The distinction between spring-sown and winter-sown varieties becomes particularly significant. Spring-sown varieties such as Durablank consistently outperformed winter-sown varieties such as MV Pelsodur and GK Julidur in terms of zinc accumulation, regardless of the environmental conditions. This suggests that spring-sown varieties may possess inherent physiological advantages that allow them to maintain or even enhance zinc uptake under suboptimal conditions, such as drought. These varieties could be better adapted to drought-prone regions where water availability is limited. In contrast, high-yielding winter-sown varieties like MV Pelsodur showed lower zinc concentrations, reflecting a possible trade-off between yield potential and nutrient density. This points to the complexity of breeding programs, which must navigate the challenge of balancing

high grain yield with improved nutritional quality, especially as climate change is expected to increase the frequency of droughts in key wheat-growing areas. Zinc-enriched grains, on the other hand, play a crucial role in improving crop productivity, particularly on zinc-deficient soils, by promoting better seedling vigor, establishing denser stands, and enhancing the plant's tolerance to environmental stresses (Bouranis, and Chorianopoulou, 2023).

The interaction between foliar application of zinc and sulfur and the genetic makeup of the durum wheat varieties further supports the potential of combining genetic selection with targeted agronomic interventions. The significantly higher grain zinc concentration observed in Durablank following foliar zinc application suggests a strong varietal capacity to uptake and translocate zinc into the grain, even under variable environmental conditions. This response indicates that foliar zinc applications, particularly in zinc-efficient varieties, could be an effective strategy to boost grain zinc levels, particularly in environments prone to micronutrient deficiencies. In contrast, high-yielding varieties like MV Pelsodur exhibited a lower capacity for zinc accumulation, even when treated with zinc and sulfur. This highlights a potential trade-off between high yield and micronutrient accumulation, similar to the yield-protein trade-off discussed earlier. High-yielding varieties may prioritize biomass accumulation over micronutrient concentration, diluting the nutrient density of the grain.

Addressing this requires an approach that balances the need for yield with the goal of enhancing nutritional quality. This trade-off is not unique to zinc but is commonly observed in cereal crops where agronomic traits related to productivity and nutritional quality often exhibit an inverse relationship (Goredema-Matongera et al., 2023). To optimize grain zinc concentration while maintaining yield, an integrated approach combining genetic selection and adjusted nutrient management is necessary. Agricultural interventions such as breeding programs should focus not only on selecting for yield potential but also for traits that enhance nutrient use efficiency and translocation within the plant. Simultaneously, the strategic application of foliar zinc, possibly combined with other nutrients such as sulfur, can further enhance the efficacy of zinc biofortification efforts. Thus, combining zinc and sulfur in fertilization strategies can enhance zinc uptake and its subsequent accumulation in the grain.

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 such as MV Pelsodur, even with zinc and sulfur applications, reveal an ongoing challenge in balancing yield with nutrient density. This highlights the complexity of breeding crops that meet both productivity and nutritional goals. As global wheat demand grows, future breeding efforts must focus not only on enhancing grain yield but also on improving the nutritional value of crops, especially in zinc-deficient regions. 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. However, the varying responses to foliar fertilization between varieties indicate the need for tailored nutrient management strategies based on the crop's genetic profile. As the results demonstrate, genetic factors play a dominant role in determining zinc accumulation, even with similar agronomic practices. This emphasizes the importance of an integrated approach that combines both genetic selection and agronomic practices to optimize zinc biofortification.

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 high-yielding varieties like MV Pelsodur highlights the ongoing challenge of balancing yield and nutritional quality. Integrating genetic selection with targeted nutrient management practices, such as foliar zinc and sulfur application, presents significant potential for improving both the productivity and nutritional value of durum wheat. This approach can play a crucial role in promoting sustainable agricultural systems and addressing food security challenges, especially as climate change introduces greater variability in growing conditions. Human zinc intake typically ranges from 107 $\mu\text{mol/day}$ to 231 $\mu\text{mol/day}$, equivalent to approximately 14–30 mg kg^{-1} (Roohani et al., 2013). Varieties such as Durablank appear promising in meeting these dietary requirements, as they accumulate 33.5–35.3 mg kg^{-1} of zinc in the grain, depending on the growing season's conditions. In contrast, varieties like MV Pelsodur and GK Julidur fall significantly below the targeted zinc levels required for human nutrition. This discrepancy indicates the superior zinc accumulation capacity of spring sown durum wheat varieties compared to winter sown

durum wheat, further indicating the need for targeted breeding programs or agronomic strategies to enhance zinc content in underperforming winter wheat varieties.

4.5. Impact of High Nitrogen Fertilization on Lodging Resistance

The analysis of variance revealed a highly significant ($p < 0.001$) effect of nitrogen management on the lodging tolerance of durum wheat varieties (Figure 22). Among the varieties studied, GK Julidur and MV Pennedur demonstrated remarkable resistance to lodging, maintaining upright posture and structural integrity even under higher nitrogen application and challenging environmental conditions. In contrast, varieties like GK Bétadur and MV Hundur were more susceptible to lodging, exhibiting severe stem bending and breakage under similar conditions (Figure 22). These highlights the genetic diversity in lodging tolerance among durum wheat varieties. Varieties such as GK Julidur and MV Pennedur likely possess genetic traits that contribute to stronger stem architecture and resilience, allowing them to better withstand the increased vegetative growth associated with higher nitrogen levels. In contrast, the vulnerability of varieties such as GK Bétadur and MV Hundur highlights the need for targeted breeding strategies aimed at improving stem strength and stress tolerance to mitigate lodging risks, particularly under elevated nitrogen fertilization.

Durum wheat varieties experiencing high levels of lodging showed a significant yield reduction of approximately 18.18%. Interestingly, the risk of lodging was less pronounced in spring-sown varieties, even when exposed to high nitrogen application rates. For drought-sensitive varieties such as Tamadur, increasing the nitrogen rate to double the recommended levels resulted in a remarkable 30.5% increase in grain yield. These results emphasise the potential of higher nitrogen rates to boost productivity in certain drought-sensitive spring-sown varieties, despite the limited benefits seen in winter-sown counterparts. However, lodging susceptibility was still strongly influenced by variations in weather conditions and crop growth dynamics across different cropping seasons. This highlights the critical need for adaptive nitrogen management strategies that are responsive to prevailing environmental conditions. A flexible, site-specific approach is essential to balance the advantages of increased nitrogen application with the risks of lodging, especially in regions where seasonal variability plays a significant role in crop performance.

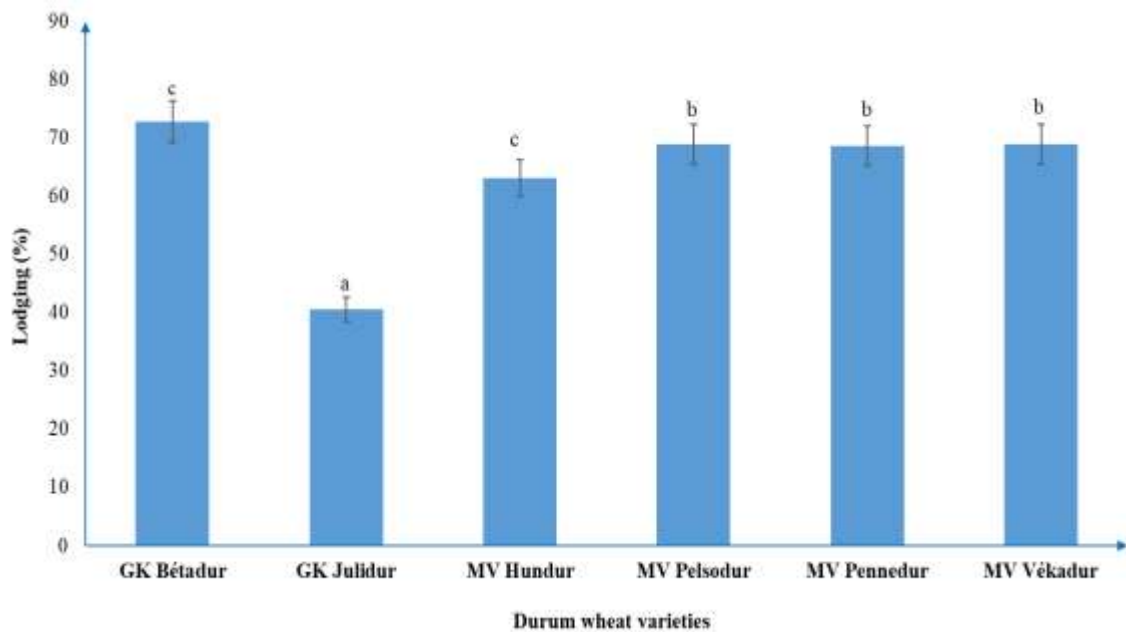


Figure 22. Depicts the disparity in lodging tolerance observed among various durum wheat varieties cultivated under winter climatic conditions, Debrecen-Látókép, 2022-2023 cropping season. Bars with the same letter indicates statistically nonsignificant

The data indicated that increased nitrogen doses negatively affected lodging tolerance, with a more pronounced decline observed at the highest nitrogen application rate of 100 kg ha⁻¹ compared to the lower rate of 60 kg ha⁻¹ (Figure 23). While nitrogen is essential for crop growth and grain yield enhancement, exceeding certain threshold levels can inadvertently increase lodging susceptibility and undermine the market value of durum wheat. A pronounced increase in lodging incidence was observed with nitrogen rates exceeding 60 kg ha⁻¹, indicating enhanced susceptibility of durum wheat to structural failure under increased nitrogen inputs. This suggests a critical threshold beyond which excessive nitrogen application exacerbates lodging risk, potentially compromising crop stability, grain yield, and nutritional profiles. A decreased lodging percentage associated with the application of 60 kg ha⁻¹ of nitrogen suggests that moderate nitrogen levels may promote optimal plant growth without compromising structural integrity. The observed increase in lodging risk associated with high nitrogen application rates can be attributed to two key factors: enhanced plant stature and a high spike density per unit area (Table 2). Hence, durum wheat-producing farmers can effectively balance yield potential with lodging risk, maximizing profitability while minimizing agronomic challenges associated with excessive nitrogen inputs by optimizing nitrogen application rates within the threshold of 60 kg ha⁻¹.

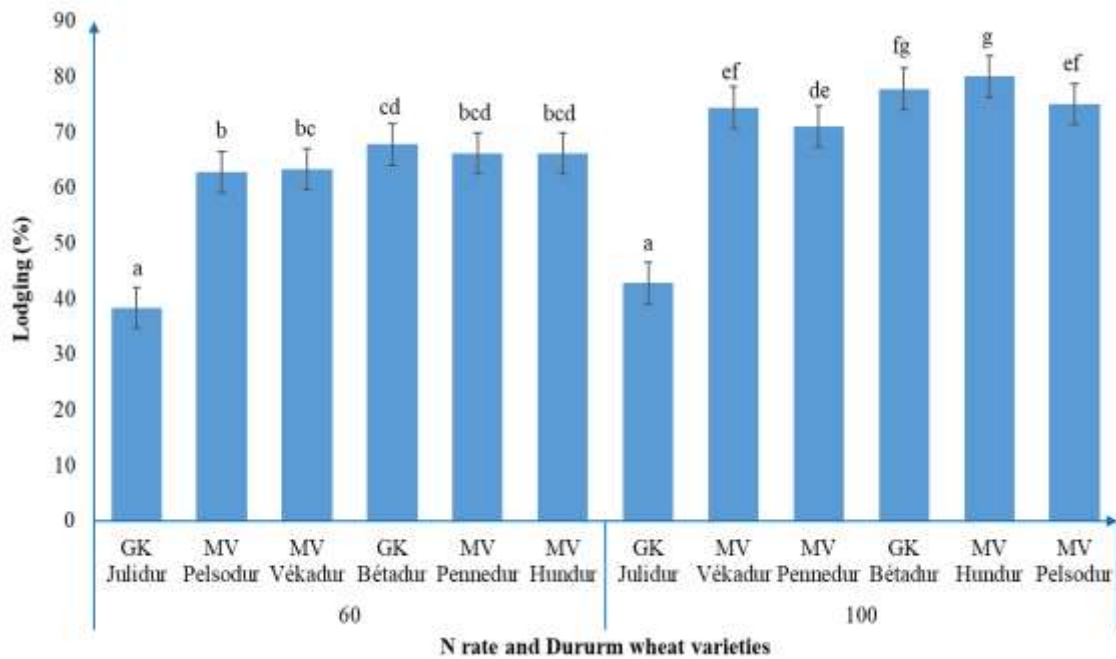


Figure 23. Illustrates lodging tolerance of various durum wheat varieties under different nitrogen application rates, Debrecen-Látókép, 2022-2023 cropping season. Bars marked with an asterisk (*) indicate statistically significant differences at the 5% probability level.

The analysis of seasonal variability revealed a statistically significant difference ($p < 0.001$) in lodging occurrences, with higher lodging percentages observed in the 2023 cropping season compared to 2022. Nitrogen application at 60 kg N ha^{-1} during the wetter season significantly reduced lodging percentages compared to the higher 100 kg N ha^{-1} rate. This suggests that lower nitrogen application rates can play a crucial role in mitigating lodging, as they may result in more favourable plant structures with increased lodging tolerance. The observed disparities in lodging risk across different cropping seasons in response to varying nitrogen rates highlights the importance of integrating environmental factors into nitrogen management strategies. This highlights the need for durum wheat producers to carefully consider local weather conditions and adjust nitrogen applications accordingly to minimize risks associated with lodging. Additionally, agronomic and breeding efforts focused on developing durum wheat varieties with optimal plant architecture such as appropriate plant height and enhanced stem stiffness are essential for reducing lodging risk and improving yield stability across diverse agro-ecological environments (Li et al., 2022). These approaches contribute to the sustainability of durum wheat cultivation, helping farmers maximize yield potential while minimizing agronomic challenges.

Integrating genetic improvements with agronomic interventions can effectively mitigate lodging risks while maximizing yield potential, ultimately contributing to the sustainability of durum wheat production and enhancing food security. The identification of durum wheat varieties with inherent lodging resistance, such as GK Julidur and MV Pennedur, holds promise for cultivar development and deployment in regions prone to lodging-related yield losses. This indicates that targeted agronomic practices, such as optimized nutrient management and crop canopy management, can complement breeding efforts in enhancing lodging resistance and improving overall crop performance. Some varieties, such as GK Bétadur and MV Hundur, despite experiencing significant lodging (100% and 95% respectively), did not exhibit a detrimental impact on grain yield due to their low structural integrity. The timing of lodging during the grain-filling stage in the 2023 cropping season further revealed that late-season lodging may have less impact on grain development and yield. Lodging that occurs after the grain-filling phase may not significantly affect grain formation, especially in varieties sensitive to lodging. Therefore, lodging does not always lead to a decrease in grain yield, as other factors such as the timing of lodging, genetic resilience of the crop, compensatory growth mechanisms, effective crop management practices, and favourable environmental conditions can mitigate the potential negative effects on yield.

4.6. Principal Component Analysis: Genotypic Performance and Trait Associations in Durum Wheat Under Divergence Environment

The principal component analysis (PCA) results highlight the intricate relationships between physio-morphological traits and grain yield across various durum wheat varieties, under different fertilizer types and levels. A notable finding from the PCA is the strong relationship between grain yield (GY) and SPAD values recorded at the tillering stage (SPAD_T), as observed in the upper-left quadrant of the biplot (Figure 24). This suggests that genotypes with higher chlorophyll content at the tillering stage tend to exhibit superior grain yields. Winter-sown varieties, such as MV Pelsodur, MV Hundur, and MV Vékadur, cluster near these traits, indicating their strong performance in terms of productivity under favourable conditions (Figure 24). These varieties demonstrate high yield potential due to their efficient chlorophyll utilization during critical early growth phases. On the other hand, early-stage canopy vigour, represented by SPAD and NDVI values measured at the booting stage (SPAD_B and NDVI_B), is located in the upper-

right quadrant, with spring-sown varieties such as Durablank and Duragold situated nearby. This implies that both varieties excel in early canopy establishment, making them well-suited for environments where early-stage growth is important, even if their final harvestable grain yield capacity may be lower compared to winter-sown durum wheat varieties. The potential to establish a canopy quickly in these environments can offer advantages in areas with early-season growth limitations.

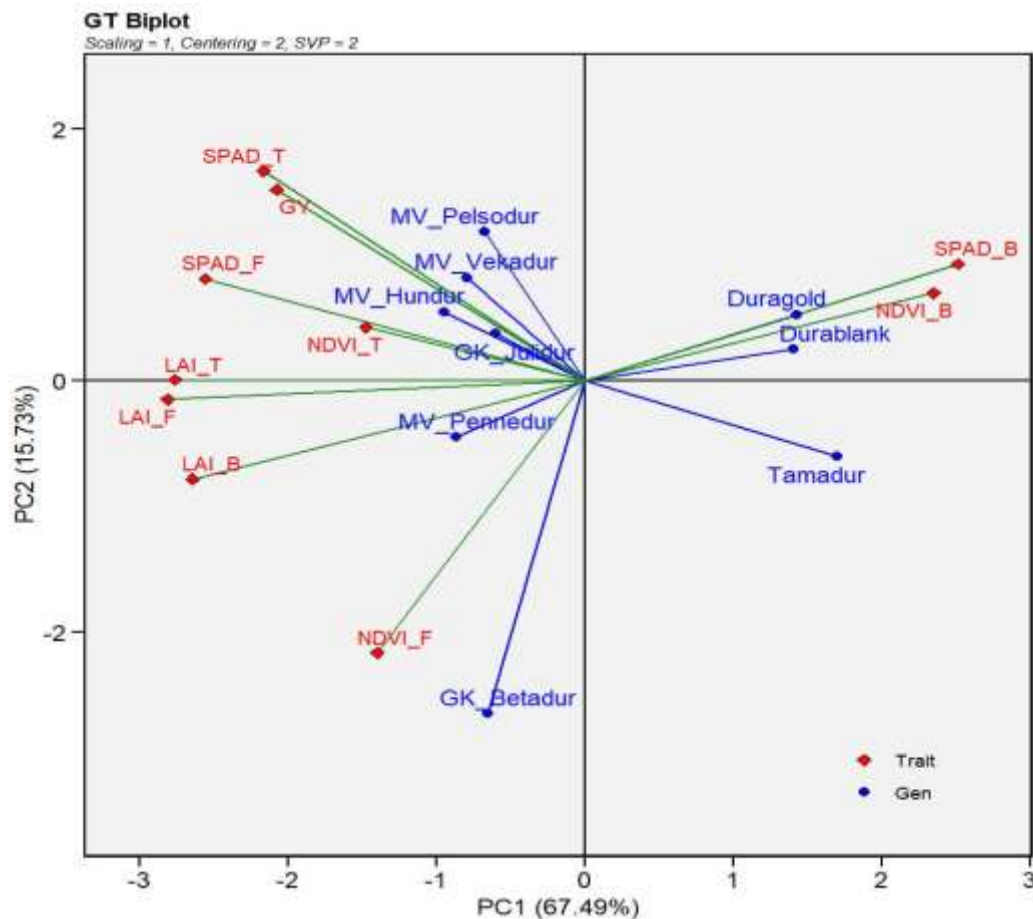


Figure 24. Illustrates PCA biplot of the relationship between durum wheat varieties (blue dots) and leaf reflectance traits (red diamonds) across different growth stages, Debrecen-Látókép, 2022-2023 cropping season. PC1: 67.49% and PC2: 15.73%, together explain 83.22% of the total variability, highlighting genotype performance and traits associations, with a focus on GY, SPAD, NDVI, and LAI.

In contrast, the drought-sensitive variety, Tamadur, located in the lower-left quadrant, is closely associated with chlorophyll content (SPAD) values recorded at the booting stage but exhibits a weaker correlation with all the recorded NDVI-related traits. This suggests that while variety Tamadur may retain chlorophyll content under stress conditions, it does not exhibit strong canopy reflectance or biomass-related traits, which are universally

associated with higher photosynthetic efficiency and overall plant vigour. The lower placement of Tamadur on the principal component reflects its vulnerability to drought or associated stress, which limits its potential for optimal growth in this conditions. Furthermore, the lower-left quadrant shows the leaf area index (LAI) traits at different growth stages, such as booting, tillering, and flowering. While these traits are correlated with early canopy establishment, their distance from grain yield and SPAD measured during the tillering stage indicates that large LAI alone may not directly contribute to maximum grain yield or chlorophyll content, particularly under drought condition. This implies the limited influence of leaf area index on yield in certain environments, highlighting the need for balanced growth across all developmental stages.

The second principal component biplot, that explaining 60.43% of the total variability (with PC1 contributing 39.86% and PC2 20.57%), further enhances the insights from the first PCA biplot by including a broader range of varieties, with an emphasis on durum wheat genetic variability and stability of leaf reflectance trait (Figure 25). The addition of confidence ellipses provides a clear visualization of durum wheat varieties clustering, variability, and stability, offering a detailed understanding of the correlation between traits and their expression among the tested varieties.

The analysis showed distinct clustering among the tested varieties, suggesting divergence in their stability and adaptability. The spring sown varieties such as Durablank and Duragold, which are tightly clustered along the second principal component, showed high stability and consistent performance across the evaluated leaf reflectance traits. In contrast, the winter sown varieties such as MV Pelsodur and MV Hundur demonstrate broader dispersion along the first principal component. This means that both varieties have greater variability and adaptability to diverse agro-ecological conditions. The close arrangement of varieties including GK Bétadur and GK Julidur implies similarities in their responses to the tested agronomic factors, emphasising potential overlap in their adaptability (Figure 25).

The confidence ellipses around the tested durum wheat varieties further showed their variability and stability (Figure 25). The smaller ellipses for variety Durablank, indicate consistent performance but limited variability, making Durablank more reliable for non-divergent environments. In contrast, larger ellipses, as seen for winter sown varieties including MV Hundur and MV Pelsodur, reflect greater variability, which may translate

to adaptability in variable or marginal conditions (Figure 25). This PCA result universally showed critical insights into varietal performance and their correlation with the evaluated leaf based trait relationships. It can be inferring that the relatively stable varieties, such as Durablank, may be prioritized for constant environments, while adaptive varieties, such as MV Pelsodur, offer flexibility for dynamic or stress-prone cropping environments. The strong loading of NDVI and SPAD measured during booting stages implies their potential as key selection criteria for breeding programs focused on improving biomass production and photosynthetic efficacy. These suggest that precision nutrient management practices, particularly nutrient and environmental optimization, could be adjusted to maximize the strengths of each durum wheat variety, ultimately contributing to improve grain yield stability and environmental adaptability in durum wheat production systems.

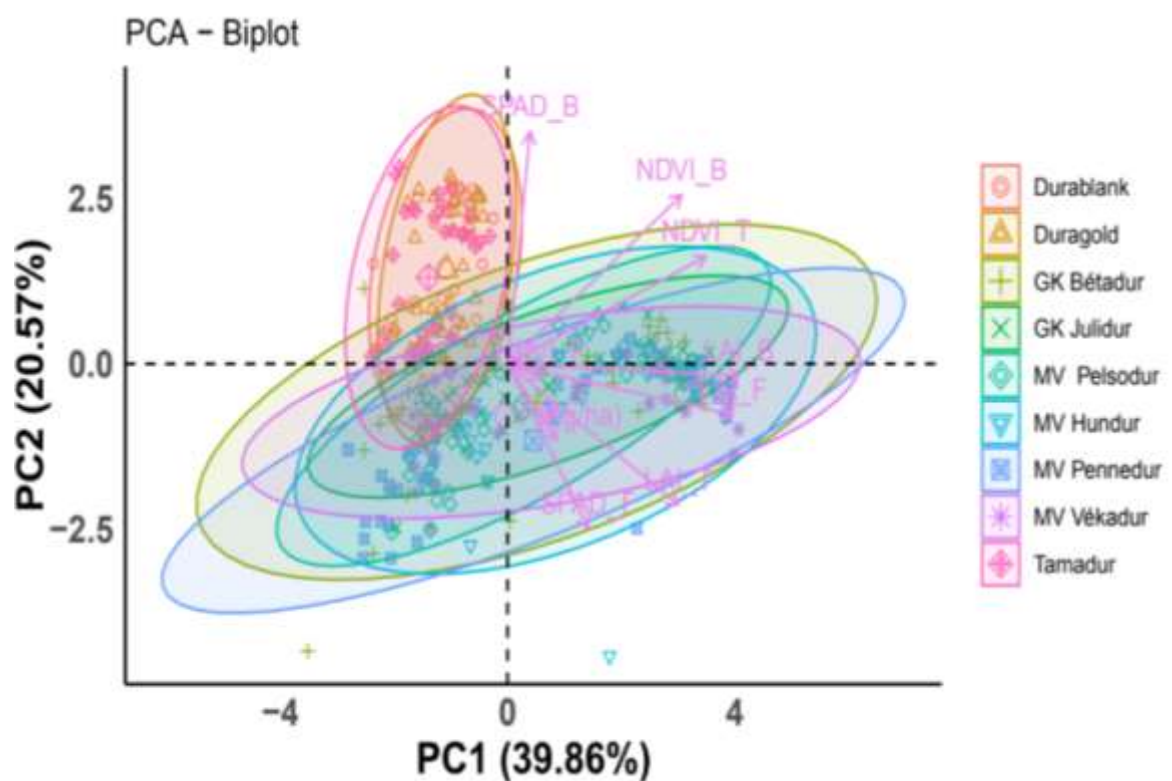


Figure 25. The relationships among durum wheat varieties, morphophysiological traits, and principal components, Debrecen-Látókép, 2022-2023 cropping season. The first principal component explains 39.86% of the variance, while the second accounts for 20.57%, capturing together about 60.43% of the total variability.

The genotype- leaf based trait correlation suggested that certain varieties, such as GK Julidur and MV Pelsodur, are closely associated with specific traits that contribute to yield and adaptability (Figure 25). The positioning of the tested durum wheat varieties in

association with trait vectors shows the extent to which specific traits influence the adaptability and performance of each tested variety. Winter sown varieties such as GK Julidur and MV Hundur, which are correlated with the NDVI_B and SPAD_B vectors, display strong correlation with high biomass production and chlorophyll content during booting stage. This means that both winter sown varieties are well-suited to environments where vegetative growth and constant photosynthetic activity are important. The central positioning of grain yield (kg ha^{-1}) on the biplot reveals its marginal influence under both principal components, indicating that grain yield was much more affected by multiple traits rather than a single dominant factor or trait. However, SPAD values measured at booting stage are positioned in the lower-left quadrant, showing a negative correlation with NDVI-related traits. This suggests a trade-off, where varieties with high NDVI may not necessarily have high chlorophyll content, indicating the complex relationships among physiological traits.

Winter sown varieties such as MV Pelsodur and GK Bétadur, which are positioned near to the central axis, display adaptability, and attaining high yield under diverse environmental conditions. However, despite its broader ellipse, MV Pelsodur clusters near the origin, which implies MV Pelsodur average performance across the measured NDVI, SPAD, LAI, and GY. Because MV Pelsodur doesn't show extreme positive or negative traits in general but rather shows a balanced response, average over the imposed factors. This mean that MV Pelsodur can perform well under divergent growing environment without unveiling extreme concentration in specific yield associated traits. A similar result for MV Pelsodur was reported, where this variety was positioned on the abscissa, indicating exceptional stability across diverse management systems while maintaining an acceptably high yield potential (Cséplő et al., 2024). The scattering of both winter (MV Pelsodur) and spring sown (Tamadur) varieties along with the first principal component further indicates potential divergence in physiological responses, with Tamadur clustering near with NDVI recorded at booting stage, confirming its adaptability to certain growing environments.

The clustering of spring sown varieties such as Durablank and Duragold near each other, and their proximity to specific trait vectors, suggests that Durablank and Duragold share comparable leaf related trait profiles. Their close-fitting grouping suggests stable performance, particularly in relative to NDVI measured during booting (NDVI_B), which is indicative of high biomass and healthier canopy. Hence, both Durablank and Duragold

could be ideal for environments where consistency and reliability are important. On the other hand, variety MV Hundur, which are more dispersed along both principal components, suggest huge variability. This means that MV Hundur can be adaptable but may display trade-offs in terms of performance across yield and yield related traits. Likewise, variety Tamadur positioned far from specific trait vectors may show weaker correlations with the measured traits, resulting in a more generalized performance.

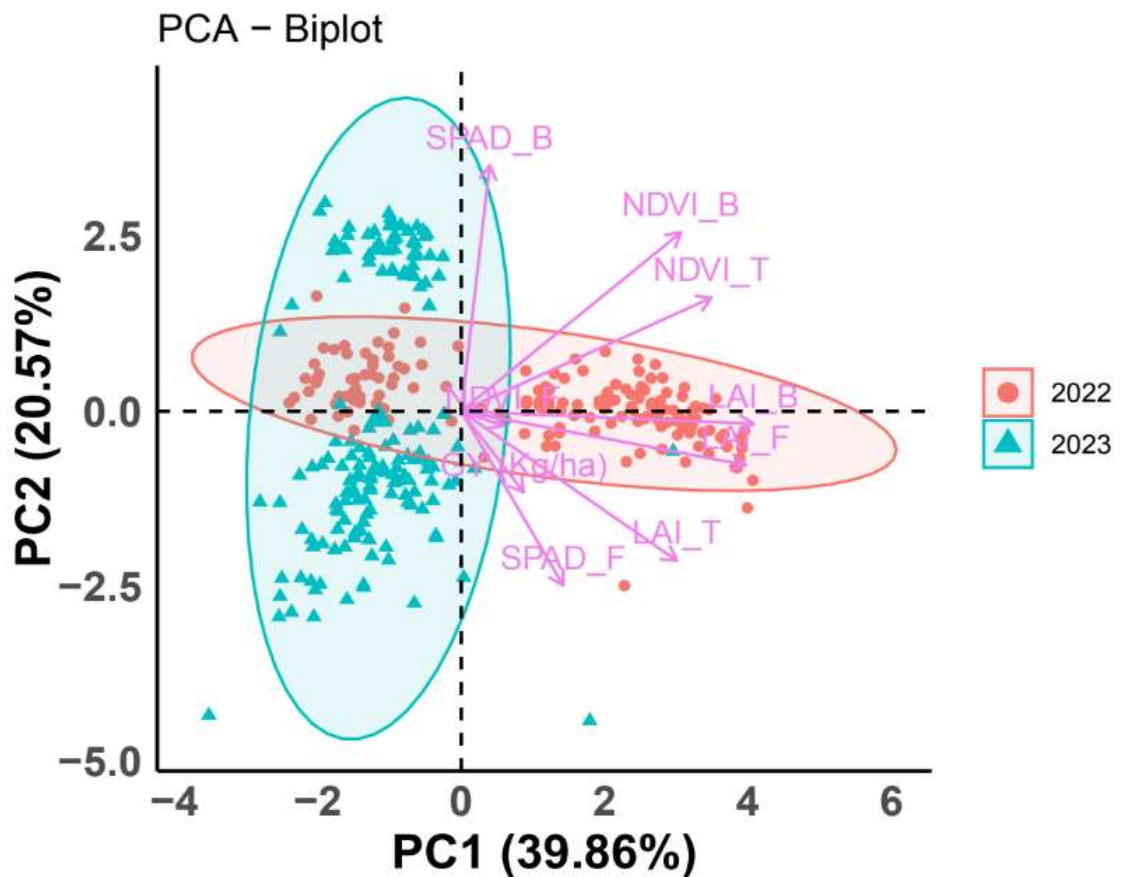


Figure 26. Illustrating the relationship between SPAD, LAI, NDVI, and nitrogen application rates across two cropping seasons (2022 and 2023), Debrecen-Látókép. The first principal component and second principal component explain 39.86% and 20.57% of the total variability, respectively. Arrows indicate the direction and magnitude of traits contributing to variability, while ellipses represent the clustering pattern of observations for each season.

The other important PCA was leaf reflectance traits and their correlation with different cropping season (2022 and 2023) (Figure 26). The PCA showed that the two principal components explain 60.43% of the total variance, with the first principal component accounting for 39.86% and primarily reflecting differences in NDVI and SPAD records. While the second principal component, explains 20.57% of the variance, captures additional variability likely associated to environmental factors or secondary yield

components. A clear separation of data points by cropping season along both principal components implies significant differences in expression of physiological traits between the two cropping seasons. The 2022 data points form a tight cluster towards the negative side of first principal component, indicating that the cropping season was marked by suboptimal growing environment, possibly due to drought stress during this particular year. This led to lower NDVI and SPAD values, implying decreased photosynthetic activity and leaf chlorophyll content. In contrast, the 2023 data points show a broader spread along the positive side of the first principal component, indicating the year was created more favourable growing environment. The wider spread and higher placement of the 2023 points along the first principal component indicate higher NDVI and SPAD values, which reflect improved photosynthetic efficiency and chlorophyll content, leading to better durum wheat growth and performance.

Morphophysiological trait vectors such as NDVI at booting, NDVI at tillering, SPAD booting, and SPAD at flowering have strong correlation with the first principal component, suggesting the importance of NDVI and SPAD at this particular growth stage in discriminating the cropping years. The higher contributions of NDVI and SPAD in 2023 suggest enhanced vegetation health and growth, likely due to the wetter conditions observed during the season. In contrast, the proximity of 2022 cropping season points to LAI recorded at booting and tillering stages indicates that these traits were relatively stable or less impacted by pedoclimatic differences between the two years.

The confidence ellipses further highlight seasonal variability. The narrower ellipse for 2022 suggests lower environmental variability but likely constrained trait expression due to adverse conditions. On the other hand, the wider ellipse for 2023 shows greater variability, potentially due to the improved growing environment allowing varietal differences to be more prominently expressed. The PCA reveals significant differences in expression yield related trait between 2022 and 2023, primarily driven by pedoclimatic difference. The 2022 growing season experienced drought stress, limiting physiological related traits, while 2023 benefitted from more favourable rainfall and temperatures, improving durum wheat productivity. This implies the importance of integrating whether data into physiological and morphological traits evaluations, emphasizing how varying growing environment can affect performance and durum wheat productivity.

The other important PCA biplot was found the correlation between durum wheat physiomorphological traits and nitrogen application rate. The varietal and physiomorphological traits distributions were affected by the different nitrogen application rates: 60 kg ha⁻¹ and 100 kg ha⁻¹. The higher (100 kg ha⁻¹) nitrogen rate, shows a wider dispersion along both principal components, indicating a greater diversity in trait responses under higher nitrogen rate (Figure 27). This result suggests that the higher nitrogen rate promoted the expression of traits associated with increased canopy development, chlorophyll content and nitrogen use efficiency. Leaf reflectance traits such as SPAD, NDVI, and LAI recorded during booting stage, were strongly aligned with the positive axes of PC1 and PC2.

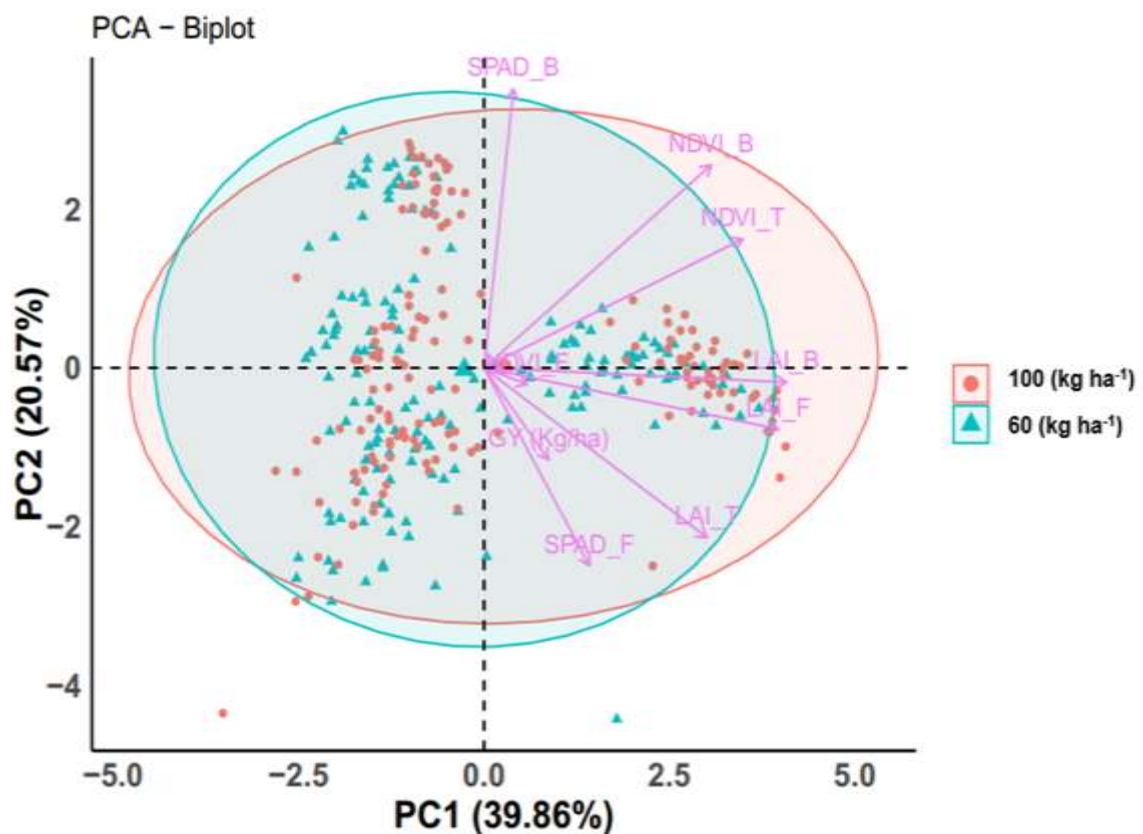


Figure 27. The effects of nitrogen application rates (60 and 100 kg ha⁻¹) on physiomorphological traits, Debrecen-Látókép, 2022-2023 cropping season. The analysis, which accounted for 60.43% of the total variance (39.86% in PC1 and 20.57% in PC2), highlights distinct patterns of trait behaviour in response to nitrogen levels.

In contrast, the lower (60 kg ha⁻¹) nitrogen rate showed a more central distribution, suggesting a less pronounced effect on expression of the studied trait compared to the higher (100 kg ha⁻¹) nitrogen rate (Figure 28). The closer proximity of SPAD at flowering

and NDVI at tillering to the higher nitrogen rate indicates that lower nitrogen rate can limit the maintenance of late-season chlorophyll content and early season canopy development. These traits, which are positively correlated with the first principal component, showed enhanced performance under higher nitrogen application rate. This indicates the importance of adequate nitrogen application for sustaining physiological functions in later developmental stages. Although LAI measured at flowering and tillering is positively correlated with the first principal component, there was no significant difference between the two nitrogen application rate. This suggest that LAI could be less sensitive to fluctuation of nitrogen rate or strongly more affected by pedoclimatic conditions of the growing environment or genetic difference. This means that there is a complexity of interactions among durum wheat varieties, cropping season, and nutrient management practices, indicating that factors beyond nitrogen fertilization rate could play a significant role in governing LAI.

The strong correlation of grain yield and LAI at booting and flowering stages along with the first principal component, mainly at the higher nitrogen rate (100 kg ha^{-1}), implies that the increased nitrogen application rate not only enhanced vegetative performance but also contributed to higher grain yield (Figure 27). Additionally, SPAD values at flowering and LAI at the tillering stage showed correlation along the second principal component, indicating variability across both nitrogen rate without favouring one rate over the other. This suggested that while higher nitrogen application rate can improve vegetative and reproductive performance, other factors may also affect LAI at different growth stages.

The elliptical grouping patterns indicate significant overlap between the nitrogen application rate. The result showed that while the higher nitrogen rate supports higher overall durum wheat performance, certain traits may still respond variably under the lower nitrogen rate. This could be indicative of diminishing returns or nitrogen saturation effects at higher application levels. The PCA result further showed the positive effect of the higher nitrogen rate (100 kg ha^{-1}) on physiomorphological traits, eventually contributing to maximum grain yield. However, the proximity and overlap of the two clusters highlight the potential for optimizing nitrogen application rate by balancing application rate with trait-specific responses to decrease environmental impacts without compromising yield and associated traits. This results provides a baseline for precision nitrogen management to specific crop growth stages and yield attributed physiomorphological traits.

4.7. A Comprehensive Analysis of Durum Wheat Traits and Their Interrelationships

4.7.1. Linking SPAD Readings, Yield, Protein Content, and Physiomorphological Traits

In the 2021 cropping season, the correlation analysis between durum wheat grain yield, protein content, agronomic traits, and physiomorphological traits revealed complex interactions, with correlations ranging from strongly positive to strongly negative depending on the specific traits being examined. These variations highlight the characteristic-specific nature of these relationships, indicating that different traits interact in unique ways under varying conditions. A strong positive correlation between NDVI and grain yield was observed, suggesting that NDVI can be a valuable tool for assessing durum wheat's health and estimating grain formation, particularly under drought conditions. NDVI's ability to assess crop status makes it especially useful in precision agriculture, offering real-time insights into durum wheat growth and productivity, which can aid in decision-making for irrigation, fertilization, and other crop management strategies.

A significant positive correlation was observed between NDVI and spike density, indicating that an increase in spike density could enhance the seasonal NDVI profile. This relationship is likely influenced by the tillering potential of the varieties and the presence of additional decumbent leaves, which contribute to improved ground coverage. In contrast, the correlation between NDVI and SPAD readings was weak, especially during the early growth stages, suggesting that chlorophyll content may not be fully captured by NDVI measurements until the crop reaches more advanced stages of development. Grain yield showed a strong correlation with NDVI values, particularly during the later developmental stages, reinforcing the idea that NDVI can be an effective predictor of grain yield, especially during the reproductive phase when yield formation is most critical. The overall data suggests that NDVI, with its strong relationship to crop health and yield, is a more reliable tool for monitoring durum wheat growth and predicting yield compared to SPAD readings, particularly in later growth stages.

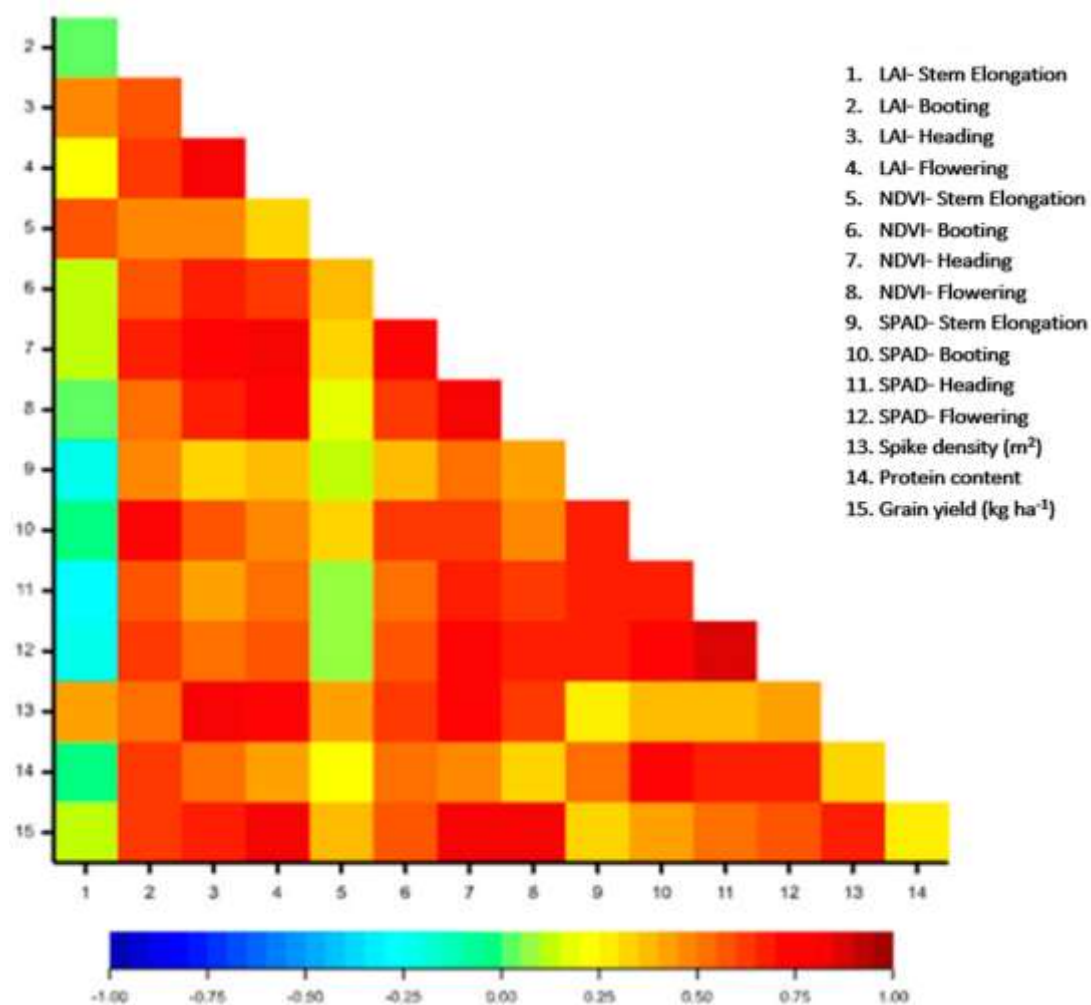


Figure 28. The correlation analysis of selected agronomic, leaf referent traits and grain yield during 2021 cropping season, Debrecen-Látókép.

The implications of these correlation results are significant for improving precision agriculture practices. NDVI emerges as a valuable tool for remote sensing, enabling real-time monitoring of durum wheat growth and aiding informed decision-making regarding crop management. While SPAD measurements are moderately correlated with grain yield, they remain beneficial for assessing early-stage growth and identifying areas that may require additional attention, particularly concerning nitrogen management. Moreover, the strong positive association between NDVI and spike density suggests that breeding programs focused on enhancing tillering capacity and leaf structure could improve yield potential, especially in environments where ground coverage and water retention are crucial. However, the weak correlation between NDVI and SPAD during early growth stages indicates that other factors, such as seedling vigour, may need to be

considered alongside these measurements to optimize predictions of crop health and yield potential in the early growing season.

The correlation analysis further revealed significant ($p < 0.05$) relationships between spike density per square meter and key physiological indicators such as LAI, NDVI, and SPAD values across different developmental stages of durum wheat (Table 20). The strength and direction of these correlations varied, offering valuable insights into how spike density influences vegetative and physiological traits during critical growth phases. A strong positive correlation was observed between spike density per square meter and LAI, particularly during the flowering stage ($R^2 = 0.901$). This suggests that as spike density increases, it contributes to a denser canopy with more decumbent leaves, enhancing ground coverage and subsequently increasing LAI values (Melash et al., 2023). Similarly, positive correlations were observed during the booting ($R^2 = 0.780$) and tillering stages ($R^2 = 0.739$), indicating that higher spike density promotes canopy fullness earlier in development, improving light interception and overall canopy health. Spike density also exhibited a strong positive correlation with NDVI, with the relationship being most pronounced during the flowering stage ($R^2 = 0.902$). This highlights that increased canopy cover due to higher spike density leads to greater vegetation health and chlorophyll content, as reflected by higher NDVI values. Although slightly weaker, the positive correlations during the booting ($R^2 = 0.776$) and tillering stages ($R^2 = 0.709$) further emphasize that robust vegetative growth driven by higher spike density enhances NDVI readings.

In contrast to LAI and NDVI, SPAD values were negatively correlated with spike density per square meter, particularly during the booting stage ($R^2 = -0.606$). This negative association may reflect a resource trade-off, where an increase in spike density intensifies competition for nitrogen, leading to a dilution effect and lower chlorophyll content in individual leaves. Interestingly, the negative correlation weakened during flowering ($R^2 = -0.178$) and turned slightly positive during tillering ($R^2 = 0.391$), suggesting that the impact of spike density on chlorophyll concentration varies across developmental stages. These results highlight the interaction between physical canopy structure and physiological health, where increased spike density contributes to better light interception and photosynthetic capacity, as evidenced by strong positive correlations with LAI and NDVI. However, the negative relationship with SPAD values emphasizes the complexity

of managing nitrogen resources, as higher spike density may necessitate careful nitrogen management to maintain chlorophyll levels and leaf functionality.

In the 2022 and 2023 cropping seasons, the correlation analysis between grain yield and various physiological indices, including LAI, NDVI, and SPAD values, revealed distinct patterns across different developmental stages of durum wheat. A strong positive correlation was observed between grain yield and LAI, with the strongest relationship occurring during the flowering stage ($R^2 = 0.648$). This finding highlights the critical role of greater canopy development during flowering in driving grain yield. The correlation was slightly weaker during the tillering ($R^2 = 0.538$) and booting stages ($R^2 = 0.502$), suggesting that while LAI remains a key determinant of yield throughout these stages, its influence is most pronounced during flowering. Similarly, grain yield exhibited a strong positive correlation with NDVI across the tillering, booting, and flowering stages. The highest correlation was observed during the flowering stage ($R^2 = 0.667$), followed by the booting ($R^2 = 0.605$) and tillering stages ($R^2 = 0.436$). NDVI, which reflects vegetation health and chlorophyll content, emerges as a reliable indicator of grain yield potential, particularly during the plant's transition into its reproductive phase. Although the correlations with NDVI were strong, they were generally slightly lower than those observed with LAI, indicating the unique and complementary roles these indices play in predicting yield performance.

The correlation between grain yield and SPAD values, which reflect chlorophyll content and indirectly indicate leaf nitrogen status, was positive but modest during the flowering ($R = 0.078$) and tillering stages ($R^2 = 0.335$). However, during the booting stage, a negative correlation was observed ($R^2 = -0.213$). The modest positive correlations during tillering and flowering suggest that while chlorophyll content contributes to grain yield, its effect is less pronounced compared to that of LAI or NDVI. In contrast, the negative correlation during the booting stage may indicate a shift in resource allocation within the plant, where higher leaf nitrogen content does not necessarily enhance yield. This could reflect nutrient imbalances, where an excessive focus on vegetative nitrogen storage detracts from reproductive development, thereby limiting yield potential.

A significant negative correlation was observed between grain protein content and both spike density (m^2) and spike length (cm). These results suggest a trade-off between yield components and grain quality. Higher spike density, often associated with increased grain

yield due to a greater number of spikes per unit area, appears to reduce grain protein content. This could be attributed to a resource dilution effect, where the available nitrogen and nutrients are distributed among a larger number of grains, lowering the protein concentration in individual grains. Similarly, longer spikes, which contribute to higher yield potential by supporting more grains per spike, may also be linked to reduced protein content. This reflects a resource allocation trade-off, where the focus on spike and grain development limits the nitrogen available for protein synthesis. While higher spike density and longer spikes are desirable for maximizing yield, their negative impact on protein content complicates efforts to meet the quality standards required for pasta and bread production.

Table 20. A summary of the correlation effects observed among the grain yield, grain protein content and physiomorphological traits of durum wheat (2022-2023).

Traits	AWL (cm)	GY (kg ha ⁻¹)	LAI			NDVI			PH (cm)	GPC (%)	SPAD			SPD (m ²)
			BS	FS	TS	BS	FS	TS			BS	FS	TS	
GY (kg ha ⁻¹)	0.249	-												
LAI Booting	0.136	0.502	-											
LAI Flowering	0.299	0.648	0.868	-										
LAI Tillering	0.087	0.538	0.834	0.763	-									
NDVI Booting	0.275	0.605	0.663	0.784	0.553	-								
NDVI Flowering	0.332	0.667	0.801	0.951	0.683	0.812	-							
NDVI Tillering	0.072	0.436	0.830	0.784	0.705	0.630	0.746	-						
PH (cm)	0.077	0.640	0.610	0.725	0.616	0.603	0.697	0.643	-					
GPC (%)	-0.013	-0.198	0.111	0.027	0.021	0.051	-0.016	0.071	-0.240	-				
SPAD Booting	-0.174	-0.213	-0.570	-0.640	-0.466	-0.467	-0.591	-0.477	-0.351	-0.130	-			
SPAD Flowering	0.038	0.078	-0.169	-0.162	-0.191	-0.128	-0.177	-0.146	-0.033	-0.160	0.479	-		
SPAD Tillering	-0.024	0.335	0.411	0.421	0.333	0.385	0.447	0.479	0.371	-0.018	-0.156	0.055	-	
SPD (m ²)	0.339	0.655	0.780	0.901	0.739	0.776	0.902	0.709	0.649	-0.034	-0.606	-0.178	0.391	-
SPL (cm)	0.024	0.551	0.460	0.530	0.540	0.526	0.525	0.483	0.578	-0.153	-0.335	-0.121	0.277	0.581

Key to abbreviations: **AWL:** Awn length (cm); **PH (cm):** plant height, **SPL (cm):** spike length, **SPD (m²):** spike density, **GPC (%):** grain protein content, **GY (kg ha⁻¹):** grain yield, **LSD_{0.05}:** Least significant difference, **CV (%):** coefficient of variation; **ST:** Stem elongation; **BT:** Booting; **HS:** Heading stage; **FS:** Flowering.

The relationship between grain protein content and NDVI revealed distinct patterns across different growth stages. NDVI, an indicator of vegetation health and biomass, showed weakly positive correlations with grain protein content during the tillering and booting stages. This suggests that better canopy health and higher biomass in the early stages may have a slight beneficial effect on protein content. However, these correlations were not strong, indicating that other factors, such as nutrient availability and environmental conditions, play a more significant role in determining protein levels. Interestingly, during the flowering stage, the correlation between NDVI and grain protein content became negative. This inverse relationship implies that as NDVI values decrease, reflecting potential declines in canopy health or changes in vegetation structure, grain protein content tends to increase. This could be due to the plant reallocating resources from vegetative maintenance to reproductive functions, enhancing protein synthesis in the grain. Alternatively, it might reflect a dilution effect, where increased canopy biomass does not proportionally enhance protein levels in the grain.

In general, the correlation results highlight notable conclusions and differences between the 2021 and 2022/2023 cropping seasons (Table 20). Leaf chlorophyll content showed a positive but modest correlation with grain yield during the flowering and tillering stages, suggesting that leaf nitrogen status contributes to yield, though not as strongly as other indicators like LAI or NDVI. However, during the booting stage, a negative correlation emerged, indicating that high leaf nitrogen status at this stage may reflect nutrient imbalances that detract from yield. Additionally, grain protein content exhibited a significant negative correlation with both spike density and spike length, highlighting a resource trade-off where higher spike density and longer spikes, while enhancing yield, may dilute available nutrients and reduce protein concentration. NDVI, a measure of canopy health and biomass, showed weakly positive correlations with protein content during the tillering and booting stages but a negative correlation during flowering. This suggests that robust canopy growth early in the season may slightly benefit protein content, whereas later in the season, resources diverted to vegetative growth may limit protein synthesis in the grain.

The differences between the two seasons highlight the role of environmental conditions in shaping these relationships. In the 2021 cropping season, harsher environmental stresses, such as drought or nutrient limitations, may have intensified the trade-offs

between yield, vegetative growth, and grain quality. This is reflected in the more pronounced negative correlations between SPAD values and yield during booting, as well as stronger trade-offs between spike density and grain protein content. On the other hand, the 2022/2023 season likely benefited from more favourable growing conditions, leading to weaker trade-offs and improved alignment between yield components and grain quality. The positive correlations between NDVI and protein content during tillering and booting stages were likely stronger in 2022/2023, reflecting healthier canopy growth and more efficient resource use. These results highlight the need for season-specific nutrient and canopy management strategies. In 2021, targeted interventions to mitigate nitrogen saturation and nutrient imbalances during critical stages, such as booting and flowering, may have been crucial to optimizing yield and quality. Meanwhile, the 2022/2023 season presented opportunities to enhance both yield and grain quality by focusing on strategies to maintain canopy health and improve nitrogen uptake efficiency.

4.7.2. Relationships Between Nutritional Characteristics in Durum Wheat Varieties

All correlations reported were statistically significant with p-values less than 0.05, except where specified otherwise. The correlation coefficients ranged from strong negative to weak positive, providing a comprehensive view of the relationships between zinc and other nutrients. The correlation analysis revealed significant relationships among the studied elements, highlighting both positive and negative associations. When examining the correlation between zinc and other nutrients, several noteworthy patterns emerged. Zinc showed a negative correlation with Al, B, Ba, Ca, Cr, Cu, Fe, K, Na, S, and Sr. These negative associations might indicate that higher levels of zinc are associated with lower levels of these nutrients in durum wheat grain, possibly due to competitive interactions or nutrient antagonism. In contrast, zinc showed no significant correlation with Mg, Mn, or Mo. This absence of correlation suggests that zinc levels do not significantly impact or are not significantly impacted by these nutrients. Zinc exhibited a weak positive correlation with P. While the positive correlation is not strong, it may still suggest a slight tendency for higher phosphorus levels to be associated with increased zinc levels in durum wheat grain.

The negative correlations between zinc and other nutrients such as calcium, magnesium, and iron suggest potential interactions that could affect nutrient management practices.

Zinc is known to have competitive interactions with other essential minerals, and understanding these relationships can help in designing more balanced fertilization strategies to optimize nutrient availability and plant health. The lack of significant correlation between zinc and magnesium, manganese, or molybdenum suggests that these nutrients may not directly influence each other's levels in durum wheat grain. However, the weak positive correlation between zinc and phosphorus could be indicative of a subtle but potentially important interaction that warrants further exploration. Investigating this relationship could provide insights into how phosphorus availability might influence zinc uptake or vice versa.

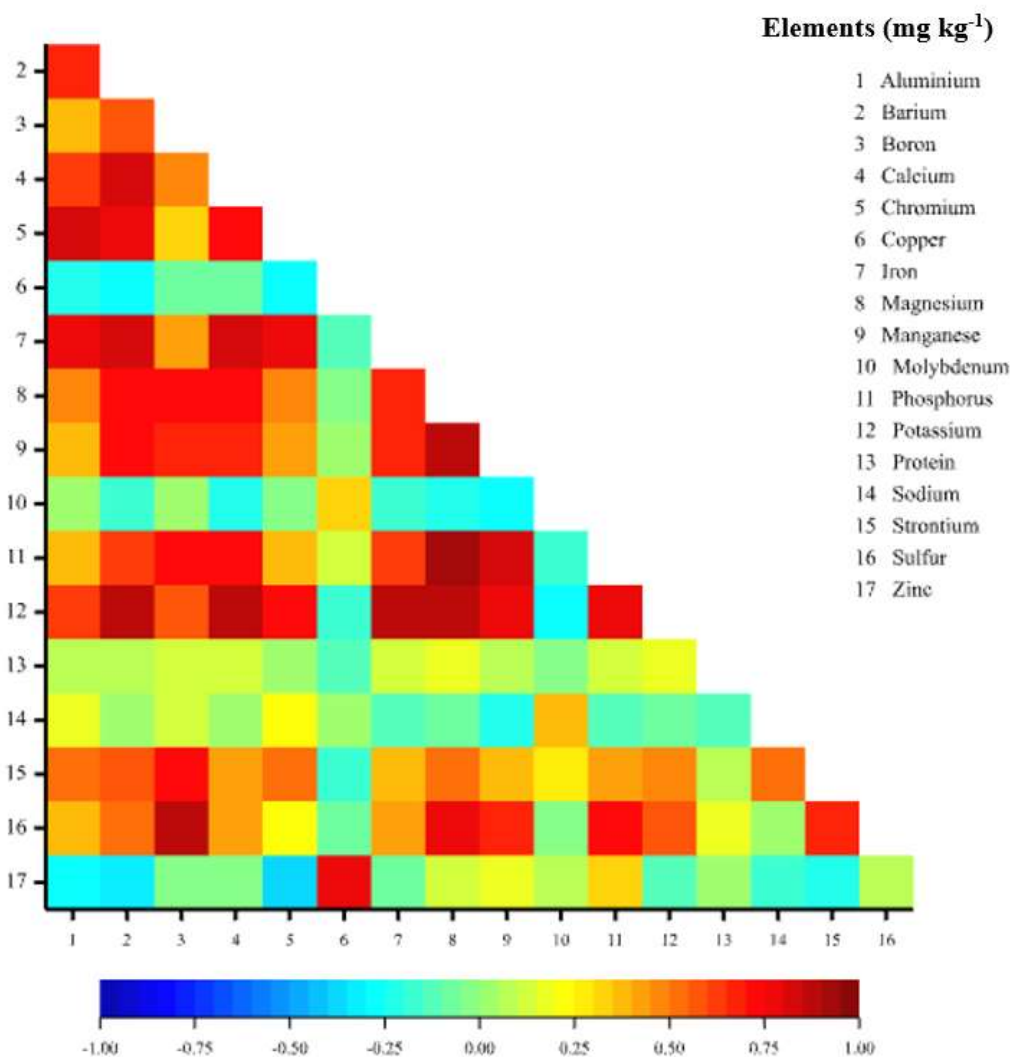


Figure 29. A correlation coefficient among the studied nutritional composition of durum wheat varieties grown under the 2022 and 2023 cropping season, Debrecen-Látókép.

Our study also investigated the relationship between potassium concentration and various nutrient traits in durum wheat grain. A significant positive correlation between potassium

and all studied traits, except for copper, which exhibited a negative correlation. It means that as potassium concentration increased, the levels of other nutrients, excluding copper, were generally higher. This suggests that potassium may play a pivotal role in enhancing the uptake or utilization of these nutrients in durum wheat. The observed positive correlation between potassium and most traits emphasizes the importance of potassium in durum wheat growth and development. Potassium is known to play a critical role in various physiological processes, including enzyme activation and osmoregulation, which can affect overall plant health and yield. The negative correlation between potassium and copper, however, warrants further investigation. It may imply that excess potassium could interfere with copper uptake or metabolism, potentially leading to deficiencies or imbalances that could impact wheat quality.

The correlation coefficients revealed strong positive relationships between sulphur and several nutrients ($R^2 = 0.75$), and strong positive associations between iron and aluminium, boron, barium, calcium, and chromium ($R^2 = 0.80$). The negative correlation between sulphur and copper was significant ($R^2 = -0.60$), while the non-significant correlation with molybdenum and sodium was reported with low correlation coefficients. Sulphur exhibited a strong positive correlation with B, Mg, Mn, P, K, and Sr. This indicates that higher sulphur levels are associated with increased concentrations of these nutrients. Additionally, sulphur showed a modest positive correlation with Al, Ba, Ca, Cr, and iron Fe, suggesting a subtler, yet still noteworthy, relationship with these elements. However, sulphur was found to have a negative correlation with Cu, implying that as sulphur concentration increases, copper levels tend to decrease.

The strong positive correlations between potassium and Fe ($R^2 = 0.78$), Ba ($R^2 = 0.72$), and calcium ($R^2 = 0.68$) indicate the substantial relationships observed (Table 19). The modest positive correlations with aluminium and chromium, though weaker, still reflect notable associations. The correlation between K and various nutrients in durum wheat grain revealed distinct patterns. Potassium exhibited a strong positive correlation with Fe, Ba, Ca, B, Mg, and Mn. Additionally, potassium showed a modest positive correlation with Al and Cr. This indicates that as potassium concentration increases, the levels of these nutrients also tend to rise, suggesting a synergistic relationship among these elements in the grain.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

As climate change continues to challenge global agricultural systems, optimizing nutrient supply, enhancing grain quality, and ensuring stable durum wheat production have become critical for achieving sustainable food security in the face of shifting environmental conditions. This study provides inclusive insights into the complex relationship between genetic variability, nitrogen fertilization, and environmental conditions in durum wheat production. The results clearly highlight the pivotal role of genetic factors in determining durum wheat yield under varying nitrogen rates, thereby emphasizing the importance of variety selection based on their inherent genetic potential for high productivity under diverse nitrogen conditions.

The variety MV Pelsodur emerged as a standout in terms of nitrogen-use efficiency, achieving the highest grain yield at the lowest nitrogen input. This exceptional performance indicates that MV Pelsodur (winter) is particularly suited for environments where nitrogen availability is limited or where sustainable farming practices are a priority. Its stable yield performance across varying nitrogen levels, particularly under low nitrogen conditions, positions it as an ideal candidate for breeding programs aimed at improving nitrogen-use efficiency in durum wheat. Conversely, other varieties, such as Tamadur (spring), demonstrated a stronger response to higher nitrogen inputs, underlining the variability in nitrogen responsiveness among durum wheat varieties. This suggests that nitrogen management strategies must be adjusted to individual varieties, taking into account their specific genetic traits and nitrogen requirements to optimize yield potential.

The study also indicates the importance of understanding genotype-by-nitrogen (G×N) interactions, which significantly influence durum wheat yield. The findings clearly demonstrate that a variety that excels under high nitrogen conditions may not necessarily perform well under low nitrogen conditions, highlighting the necessity for more targeted and variable nitrogen management practices. For instance, while varieties like MV Pelsodur thrive under low nitrogen inputs, others, such as Tamadur, require higher nitrogen levels to reach their yield potential. This variability in nitrogen responsiveness further emphasizes the need for adjusted fertilization strategies that consider both the

genetic makeup of the varieties and the environmental conditions in which they are grown.

Furthermore, the study delves into the effect of zinc and sulphur fertilization on durum wheat productivity, revealing that their effectiveness is heavily influenced by pedoclimatic factors, with notable variations observed across different cropping seasons. In the 2022 season, both zinc and sulphur applications significantly boosted grain yield, with zinc contributing to a 5.25% increase and sulphur providing an even more substantial 14.52% increase in yield. However, in the subsequent 2023 season, although the application of these nutrients still resulted in higher yields, the difference was not statistically significant, indicating that environmental factors such as rainfall, temperature fluctuations, and soil conditions played a crucial role in modulating the effectiveness of nutrient applications. These seasonal differences further emphasize the importance of considering specific pedoclimatic conditions when planning nutrient management strategies. The findings suggest that a more flexible and adaptive approach to nutrient management, which accounts for both seasonal and environmental variability, would maximize nutrient use efficiency and ensure optimal yield outcomes in durum wheat production.

The study also highlighted the synergistic effects of nitrogen and sulphur applications, particularly in the context of varying environmental conditions. The interaction between these nutrients and varietal differences significantly influenced grain yield, with some varieties, such as MV Pelsodur, achieving the highest grain yield under a low nitrogen rate combined with sulphur application in the 2023 cropping season. This indicates that nutrient optimization, especially the strategic use of nitrogen and sulphur, could enhance durum wheat yield without requiring excessive nitrogen inputs. However, the study also cautioned that excessive nitrogen application beyond a certain threshold (100 kg ha^{-1}) may lead to nitrogen saturation, which could not only fail to improve yields but also result in detrimental environmental effects, such as nitrate leaching and nitrous oxide emissions. These environmental concerns reinforce the need for a balanced nitrogen application strategy that minimizes the negative impacts of excess nitrogen on the environment while optimizing yield.

Additionally, the study found that high spike density did not always correlate with higher grain yields, with varieties like MV Pelsodur achieving the highest yield despite having

the lowest spike density. This suggests that factors such as spike length, SPAD, and NDVI are more critical determinants of yield than spike density alone. The ability of MV Pelsodur to maintain high yields despite lower spike density may be attributed to its longer spike length, which compensates for the lower number of spikes. These findings emphasize the importance of considering multiple yield components, rather than focusing solely on spike density, when optimizing nitrogen application for sustainable durum wheat production.

Moisture availability was identified as another crucial factor influencing durum wheat productivity, particularly in drought-prone environments. The study found that nitrogen application, while beneficial, was not a limiting factor during the dry 2022 season. This suggests that effective water management strategies are essential for maximizing durum wheat productivity in dryland regions, as moisture availability interacts with nitrogen dynamics to influence crop resilience. These findings highlight the need for integrated nutrient and water management practices that account for both nutrient availability and water supply, particularly in regions facing increasing water scarcity due to climate change.

The analysis of vegetation indices, such as NDVI, revealed significant variability in responses to nitrogen application, which varied according to varietal differences and developmental stages. While spring-sown varieties responded more favourably to higher nitrogen levels, winter-sown varieties exhibited a muted response, suggesting that their adaptation to cooler, wetter conditions limits their nitrogen-use efficiency. The study also indicated that nitrogen application beyond 100 kg ha⁻¹ did not improve NDVI values, potentially leading to nitrogen saturation or stress, which underscores the need for more precise and targeted nitrogen management strategies that consider variety type, growth stage, and environmental conditions.

In terms of grain protein content, the study found significant variation across varieties and years, with the drier 2022 season exhibiting a 13.39% variation, compared to a 7.22% variation in the more favourable 2023 season. This highlights the critical interaction between environmental conditions, particularly moisture availability, and genetic factors in determining grain protein content. The drier conditions of 2022 amplified genetic differences, as stress-adapted varieties exhibited greater variability, while the more favourable conditions of 2023 led to more uniform protein content across varieties. This

indicates the dominant role of environmental factors in determining grain quality under optimal conditions, while stress conditions can accentuate genetic variability.

The study also analysed the interaction between cropping years and varietal differences in grain zinc concentration, revealing that spring-sown varieties like Durablank were more effective at accumulating zinc, particularly under drought conditions. Durablank achieved the highest zinc concentrations in both the dry 2022 season and the wetter 2023 season, suggesting its superior ability to accumulate zinc compared to winter-sown varieties like MV Pelsodur and GK Julidur. The findings indicate that spring-sown varieties may be better suited for zinc biofortification, especially in dry conditions, and highlight the significant impact of environmental factors on nutrient uptake.

Additionally, principal component analysis (PCA) and genotype-leaf trait correlations revealed important insights into varietal performance and their association with key physiological traits such as NDVI and SPAD values. Varieties like Durablank, with smaller confidence ellipses, demonstrated consistent performance, making them reliable for stable environments, while larger ellipses for varieties like MV Pelsodur suggested greater adaptability to variable or marginal conditions. The strong loading of NDVI and SPAD at the booting stage further emphasizes their potential as key selection criteria for breeding programs focused on improving biomass production, photosynthetic efficiency, and overall yield stability.

In generally, this study emphasizes the importance of variety-specific nutrient management strategies that account for genetic traits, environmental conditions, and seasonal variability. The findings suggest that optimizing nitrogen, sulphur, and zinc fertilization, alongside improved water management practices, will be crucial for achieving sustainable and high durum wheat yields. Future breeding programs must prioritize nitrogen-use efficiency and adaptability to environmental variability, ensuring that durum wheat production systems are both productive and environmentally sustainable in the face of global challenges such as climate change and resource limitations.

5.2. Recommendations

Based on the results of this study, several key recommendations can be made to optimize durum wheat production, improve nitrogen and nutrient management, and enhance sustainability in the face of climate change and environmental challenges. These recommendations aim to enhance productivity while minimizing environmental impact and improving the nutritional quality of durum wheat:

1. **Prioritize Nitrogen-Use Efficient Varieties:** Winter-sown varieties such as MV Pelsodur, which exhibited high nitrogen-use efficiency and high grain yield at lower nitrogen rates, should be prioritized for cultivation in regions with limited nitrogen resources or where sustainability is a key consideration. These varieties present opportunities for reducing fertilizer inputs while maintaining productivity, thus minimizing the environmental impact associated with excessive nitrogen application, such as nitrate leaching and greenhouse gas emissions.
2. **Adjust Nitrogen Fertilization Based on Variety and Environmental Conditions:** The study demonstrated significant genotype-by-nitrogen (G×N) interactions, emphasizing the need for adjusted nitrogen fertilization strategies. Spring-sown varieties like Tamadur, which respond positively to higher nitrogen rates, may require higher inputs to optimize yields, while varieties like MV Pelsodur can achieve optimal yields with lower nitrogen inputs. Therefore, agronomists, agricultural development agents and durum wheat producing farmers should adopt a variety-specific approach to nitrogen fertilization, adjusting nitrogen rates based on the variety's responsiveness and the specific environmental conditions of the growing season.
3. **Optimize Nutrient Applications (Zinc and Sulphur) Based on Seasonal Conditions:** The findings on the beneficial impact of zinc and sulphur applications highlight the importance of considering seasonal and environmental factors when planning nutrient management. In years with less favourable climatic conditions (e.g., 2022), foliar applications of zinc and sulphur significantly improved yield, whereas their effect was less pronounced in favourable years (e.g., 2023). Therefore, zinc and sulphur application should be prioritized during seasons with less favourable weather to maximize yield and

ensure nutrient optimization. Furthermore, nutrient management strategies should be flexible and adjusted based on annual weather patterns to enhance efficiency.

4. **Incorporate Moisture Availability into Fertilization Plans:** Moisture availability was identified as a key factor in determining durum wheat growth and productivity, especially under drought conditions. In drier seasons, nitrogen alone was insufficient to improve yield, indicating that integrated water management strategies are necessary for enhancing productivity. Agronomist and farmers should consider the interaction between water availability and nitrogen application and incorporate irrigation or rainwater harvesting practices in areas prone to drought, in conjunction with nitrogen management, to improve yield and sustainability.
5. **Encourage the Use of Spring-Sown Varieties for Biofortification in Drier Regions:** The study's findings regarding zinc biofortification indicate that spring-sown varieties, such as Durablank, exhibit higher grain zinc concentrations, particularly in drier cropping season. These varieties should be promoted in regions where micronutrient deficiencies, such as zinc, are prevalent, as they provide an opportunity for addressing nutritional deficiencies while improving durum wheat yield. Spring-sown varieties may offer a more suitable option for biofortification programs targeting micronutrient deficiencies.
6. **Enhance Breeding Programs Focused on Nitrogen-Use Efficiency and Stress Tolerance:** Breeding programs should focus on improving the genetic traits of durum wheat, particularly nitrogen-use efficiency, stress tolerance, and nutrient biofortification potential. Varieties that can perform well under low nitrogen conditions, such as MV Pelsodur, should be further developed and promoted for areas with limited fertilizer access. Additionally, breeding for drought tolerance and resilience to environmental stresses, such as high temperatures and water shortages, will be critical for ensuring the long-term sustainability of durum wheat production in the face of climate change.
7. **Adopt Precision Agriculture Practices:** The use of canopy reflectance sensors and other precision agriculture tools can be valuable for optimizing fertilizer applications and improving nitrogen-use efficiency in durum wheat production. Precision agriculture allows for real-time monitoring of crop health, nutrient

status, and environmental conditions, enabling agricultural practitioners to apply fertilizers in a more targeted manner. This approach will improve nutrient use efficiency, reduce wastage, and minimize the environmental footprint of durum wheat cultivation.

8. Promote Education and Extension Services for Sustainable Fertilizer Use:

Extension services should play an essential role in disseminating knowledge on sustainable nutrient management practices. Educating farmers on the benefits of using nitrogen-efficient varieties, optimizing nutrient applications based on seasonal conditions, and incorporating water management practices will be key to achieving high and sustainable durum wheat yields. Training programs should be developed to enhance farmers' understanding of nutrient interactions, crop physiology, and the importance of environmentally friendly farming practices.

Adopting these recommendations, can improve both productivity and sustainability of durum wheat, reducing the environmental impact of farming practices while ensuring that global food demands are met. Integrating genetic research, innovative nutrient management practices, and climate-resilient cultivation strategies will be essential for maintaining long-term food security in the face of ongoing challenges such as climate change and resource limitations.

6. 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 favourable 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. 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 results 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.

7. PRACTICAL UTILIZATION OF RESULT

This section presents research results can be effectively applied to enhance durum wheat production. The insights provided here serve as valuable guidance for producers and agronomists, enabling them to make informed decisions about nutrient management strategies adjusted to their specific objectives. Through embracing these practical applications, stakeholders can optimize both yield and grain quality, paving the way for more sustainable agricultural practices. These efforts will not only boost productivity but also contribute to improved economic outcomes for farmers, ultimately ensuring a more resilient future for durum wheat cultivation.

1. The use of remote sensing technologies, such as NDVI profiling, can be valuable for agronomists in assessing the health and vigour 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.

8. SUMMARY

The selection of an optimal quality improvement strategy for durum wheat is essential, particularly given the diverse requirements for industrial and local food products. A promising approach focuses on effective nitrogen fertilization management combined with the use of nutrient-efficient varieties. Appropriate nitrogen fertilization plays a crucial role in enhancing grain yield and technological traits. This management strategy aims to achieve maximum yield production based on the applied nitrogen rate, improve protein content, and enhance the elemental composition of the grains. However, it is noteworthy that the total nitrogen amount required to achieve acceptable grain protein content is significantly higher than what is necessary solely for increasing grain yield and associated traits. Therefore, determining the optimal nitrogen fertilizer rate for specific locations and cropping seasons necessitates a careful balance between achieving grain yield and ensuring the quality of the end products.

Varieties such as Durablank, despite lower chlorophyll content, outperformed others such as Duragold, highlighting the importance of stress tolerance and nutrient use efficiency. Chlorophyll concentration, measured via SPAD readings, proves to be an effective indicator of nitrogen status, especially under drought stress. Higher SPAD values, particularly during the heading stage, correspond to improved yield and protein content, with varieties maintaining elevated SPAD levels showing greater drought tolerance and yield stability. Nitrogen application significantly increases SPAD readings, with peak values recorded at the heading stage, providing a benchmark for optimal nitrogen use. This timing is critical for ensuring nitrogen inputs meet the crop's physiological needs without excess application, particularly in water-limited environments. Despite spike density contributing to yield formation, leaf chlorophyll content had a more pronounced effect on yield under moisture stress. The interaction between nutrient supply, environmental conditions, and genetic factors implies the complexity of durum wheat productivity. In drought-prone regions, strategies that enhance nitrogen use efficiency and maximize yield stability while minimizing environmental impacts are essential for sustainable durum wheat production.

The interaction between nitrogen fertilizer rates and durum wheat varieties reveals significant genetic variability in grain yield, with varieties including MV Pelsodur and MV Hundur showing exceptional efficiency at lower nitrogen rates (60 kg ha⁻¹). In contrast, Tamadur required higher nitrogen levels (100 kg ha⁻¹) to achieve optimal

productivity. This variability highlights the importance of tailoring nitrogen management strategies to specific varieties. The 43.4% difference in grain yield between MV Pelsodur and Tamadur at the lowest nitrogen rate indicating the genetic predisposition of certain varieties for better productivity and nitrogen-use efficiency, suggesting that some varieties are inherently more adaptable to nitrogen fertilization. Tamadur's reduced performance at lower nitrogen rates may indicate genetic limitations or lower responsiveness to nitrogen, resulting in lower productivity.

The observed variation in grain yield among the tested durum wheat varieties across different nitrogen rates suggests that not all varieties respond uniformly to nitrogen fertilization. For instance, MV Pelsodur consistently performed well across both nitrogen rates (60 and 100 kg ha⁻¹), with minimal difference in yield, highlighting its robust performance and efficient nitrogen use. This implies the potential for breeding and selecting varieties like MV Pelsodur that can maintain high yields across varying nitrogen conditions, which is crucial for improving grain yield stability and optimizing nitrogen-use efficiency. Such adaptability is essential for sustainable durum wheat production, especially in environments where nitrogen availability fluctuates.

The analysis also reveals significant differences in nitrogen response based on planting dates. Spring-planted varieties such as Durablank and Tamadur showed significant yield improvements with higher nitrogen rates, indicating greater nitrogen demand during their growth phases. In contrast, winter-planted varieties achieved higher overall yields but exhibited less pronounced responses to increased nitrogen, possibly due to reaching a nutrient uptake threshold. This suggests that nitrogen management should be adjusted not only to variety but also to planting season, with spring-planted varieties requiring more nitrogen for optimal growth, while winter-planted varieties may need balanced applications to avoid excessive fertilization. Further analysis highlights the importance of balanced nitrogen application rates, particularly for winter-planted varieties such as GK Julidur and GK Bétadur, which experienced yield reductions under high nitrogen rates. Excessive nitrogen application can lead to diminishing returns, even reducing yield in some cases. This result emphasizes the critical need for precise nitrogen management to avoid over-fertilization, which could harm yield potential and lead to environmental consequences. Leveraging genetic variability in durum wheat varieties can maximize grain yield while maintaining sustainable cropping systems.

Additionally, the interaction between nitrogen levels and environmental conditions, such as growing season climate, significantly impacts grain yield. During wetter years, excessive nitrogen application can lead to slight yield reductions, while in drier years, increased nitrogen rates may enhance productivity. This suggests that nitrogen management strategies should be flexible, adjusting nitrogen levels according to the season's moisture conditions to optimize yields. Nitrogen requirements are not static and must be adapted to the specific needs of the growing season, especially under changing climate conditions. In general, nitrogen application rates, genetic variation among durum wheat varieties, and environmental factors all play crucial roles in determining yield outcomes. Varieties such as MV Pelsodur have shown consistent high performance across nitrogen rates, while others, like Tamadur, have greater nitrogen requirements for optimal productivity.

The complex interaction between nitrogen availability, genetic traits, and environmental factors, such as seasonal climate and planting dates, indicates the importance of tailored nitrogen management strategies. Optimizing nitrogen use efficiency, enhancing varietal selection, and adjusting management practices to the specific growing conditions can further support more sustainable and productive durum wheat cropping systems. The spring-type varieties responded positively to higher nitrogen rates, enhancing productivity under varied moisture conditions. In contrast, winter-type varieties exhibited reduced productivity with excessive nitrogen, particularly under sufficient moisture. It is, therefore, recommended that nitrogen application strategies could be adjusted based on specific durum wheat varieties and environmental conditions, ensuring that spring-type varieties receive adequate nitrogen to maximize yield, while winter-type varieties are managed with caution to prevent negative impacts from excessive nitrogen. Agronomists and other stakeholders should adjust nitrogen management strategies based on durum wheat type and prevailing environmental conditions to effectively optimize productivity.

The effectiveness of zinc and sulphur fertilization on durum wheat grain yield is significantly influenced by the pedoclimatic conditions of specific cropping seasons. In 2022, both nutrients had a positive impact on yields, with zinc increasing yield by 5.25% and sulphur by 14.52%. However, in the 2023 cropping season, although yields were higher with zinc and sulphur applications, the differences were not statistically significant ($p < 0.05$), indicating that environmental factors such as rainfall, temperature, and soil conditions can affect nutrient effectiveness and yield responses. This inconsistency in

yield responses across seasons indicates the need for adaptive nutrient management strategies that consider specific environmental conditions. Relying solely on nutrient supplementation without accounting for pedoclimatic influences may limit potential yield improvements. The interaction between durum wheat varieties, nutrient applications, and growing seasons significantly affects grain yield. In 2023, the variety MV Pelsodur achieved the highest yields with sulphur (8558.22 kg ha⁻¹) and zinc (8464.74 kg ha⁻¹), suggesting effective nutrient utilization under favourable conditions.

In contrast, during the 2022 cropping season, MV Vékadur reached a maximum yield of 7540.24 kg ha⁻¹ with foliar sulphur fertilization and 6970.35 kg ha⁻¹ with zinc application, indicating a different response to nutrient treatments compared to MV Pelsodur. This variation may stem from differences in growing conditions and nutrient utilization mechanisms. Furthermore, the differing effectiveness of nutrients between the two seasons can be attributed to specific pedoclimatic conditions experienced. The higher rainfall and optimal temperatures in 2023 likely enhanced nutrient uptake and utilization, while the more challenging conditions in 2022 necessitated sulphur's critical role in supporting growth and yield. Therefore, fine-tuning nutrient applications to align with specific environmental conditions and cropping seasons is essential for optimizing productivity and nutrient efficiency in durum wheat production.

The varieties-trait relationships identified in the PCA highlight the adaptability of certain varieties and suggest opportunities for targeted breeding and management. The alignment of certain varieties with specific traits indicates their relative strengths; for instance, varieties aligned with NDVI and SPAD measured during booting stages are likely to perform well in biomass-related traits, while others may excel in grain yield. The strong association of NDVI and SPAD measured with specific varieties indicates their importance in breeding programs focused on improving biomass production, stress resilience, and photosynthetic efficiency. At the same time, the balance between multiple traits, as seen in varieties with strong grain yield potential, suggests that a holistic management approach is crucial for optimizing genotypic performance. These PCA results emphasize the need to integrate trait-specific management practices and varietal selection to enhance durum wheat production across diverse environmental conditions.

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10. LIST OF PUBLICATIONS



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Subject: PhD Publication List

Candidate: Anteneh Agezew Melash
Doctoral School: Kálmán Kerpely Doctoral School
MTMT ID: authors10095122

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.
Agrártud. közl. 2022 (2), 9-20, 2022. ISSN: 1587-1282.
DOI: <http://dx.doi.org/DOI: 10.34101/ACTAAGRAR/2/11053>
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.
Agrártud. közl. 1, 111-121, 2022. ISSN: 1587-1282.
DOI: <http://dx.doi.org/10.34101/actaagrar/1/10428>

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.
Life (Basel). 13 (3), 1-20, 2023. EISSN: 2075-1729.
DOI: <http://dx.doi.org/10.3390/life13030824>
IF: 3.2
4. **Melash, A. A.**, Bogale, A. A., Migbaru, A. T., Chakilu, G. G., Percze, A., Ábrahám, É. B., Mengistu, D. K.: Indigenous agricultural knowledge: A neglected human based resource for sustainable crop protection and production.
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5. **Melash, A. A.**, Bogale, A. A., Bytyqi, B., Nyandi, M. S., Ábrahám, É. B.: Nutrient management:bas a panacea to improve the caryopsis quality and yield potential of durum wheat (*Triticum turgidum* L.) under the changing climatic conditions.
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6. **Melash, A. A.**, Bogale, A. A., Mengistu, S. G., Aberra, D. A., Tsegay, A., Mengistu, D. K.: Sustainable management practices for durum wheat production: Analyzing specific agronomic interventions on productivity, grain micronutrient content, and quality.
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7. **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.
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8. **Melash, A. A.**, Mengistu, D. K., Bogale, A. A., Mengistu, S. G.: A dataset of Agronomic Biofortification and Seeding rate - by - Location effects on Grain Mineral concentration, End-use quality and Agro-phenological traits of Durum wheat Genotypes.
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DOI: <http://dx.doi.org/10.1016/j.dib.2021.106899>
9. **Melash, A. A.**, Mengistu, D. K.: Improving Grain Micronutrient Content of Durum Wheat (*Triticum turgidum* var. durum) through Agronomic Biofortification to Alleviate the Hidden Hunger.
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DOI: <http://dx.doi.org/10.1155/2020/7825413>

Foreign language abstracts (2)

10. **Melash, A. A.**, Ábrahám, É. B.: Nutrient Management Practices for Enhancing Productivity, Nutritional Compositions, And Quality in Durum Wheat.
In: 21st Wellmann International Scientific Conference Book of abstracts / felelős kiadó Edit Mikó, szerk. Ingrid Melinda Gyalai, Szilárd Czóbel, University of Szeged Faculty of Agriculture, Hódmezővásárhely, 23, 2024. ISBN: 9789633069806
11. **Melash, A. A.**, Ábrahám, É. B.: Synergistic Improvement of Yield and Grain Protein Content of Durum Wheat Through Co-Fertilization of Multiple Nutrients.
In: 19th Wellmann International Scientific Conference : Book of abstract, Ed.: Kiss Orsolya, University of Szeged Faculty of Agriculture, Hódmezővásárhely, 59, 2022. ISBN: 9789633068601





List of other publications

Foreign language scientific articles in international journals (6)

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Plants-Basel. 12 (4), 1-18, 2023. EISSN: 2223-7747.
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IF: 4
13. Bogale, A. A., **Melash, A. A.**, Percze, A.: Symbiotic and Asymmetric Causality of the Soil Tillage System and Biochar Application on Soil Carbon Sequestration and Crop Production.
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Zemdirbyste. 109 (2), 107-114, 2022. ISSN: 1392-3196.
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15. Kutasy, E., Bódi, E., Virág, I. C., Forgács, F., **Melash, A. A.**, Zsombik, L., Nagy, A., Csajbók, J.: Mitigating the Negative Effect of Drought Stress in Oat (*Avena sativa* L.) with Silicon and Sulphur Foliar Fertilization.
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11. DECLARATION

I prepared this dissertation within the framework of the Kálmán Kerpely Doctoral School at the University of Debrecen to fulfil the requirements for obtaining a Doctor of Philosophy (PhD) in Crop Production and Horticultural Science from the University of Debrecen.

Debrecen, 2025.....

.....

Signature of the Doctoral Candidate

DECLARATION

I hereby certify that **Anteneh Agezew Melash**, a doctoral candidate from 2021 to 2025 within the framework of the aforementioned doctoral school, has conducted the research under my guidance and supervision. The contributions and results presented in the dissertation represent the independent work of the candidate. I fully endorse the acceptance of this dissertation.

Debrecen, 2025.....

.....

Signature of the Supervisor

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