UNIVERSITY OF DEBRECEN

KÁLMÁN KERPELY DOCTORAL SCHOOL

Head of Doctoral School
Dr. Imre Holb
university professor, doctor of Hungarian Academy of Science

Supervisor:

Prof. Dr. Adrienn Kakuszi-Széles

University professor

Evaluation of yield and quality of maize (Zea mays L.) hybrids of different genotypes

by:

Ibtissem Balaout

PhD candidate

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Evaluation of yield and quality of maize (Zea mays L.) hybrids of different genotypes

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Dr............................ ....

Dr............................ ....

The evaluation committee:

Chairperson: Dr............................. . ...

Members: Dr............................. ....

Dr............................. ....

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1. Introduction

Maize (Zea *mays L.*), is one of the three major cereals that shaped global civilization. With over 1.24 billion tonnes produced on about 200 million hectares, it is the World’s most widely grown cereal, exceeding wheat and rice (Erenstein et al., 2022; Faostat, 2025) (Figure 1). It is cultivated in every continent except Antarctica (Orhun, 2013). Global maize production has risen sharply since 1961 (Figure 1), with North America leading, followed by Asia, South America, and Europe. The United States of America represents the world leader with an annual production of 389.69 million tonnes in 2023, followed by China with 288.84 million tonnes and Brazil with 131.95 million tonnes (Table 1). Within the EU, Hungary, France, and Romania are among the main producers.

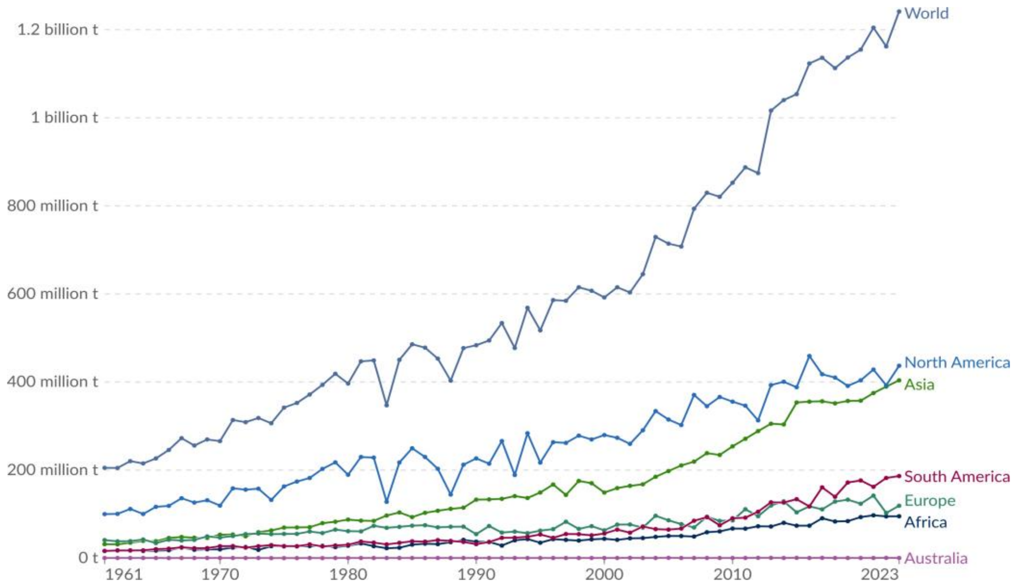

Figure 1. Maize production in the world and main regions (1961 to 2023) (**Source**: Our World in Data, Accessed on 11 May 2025. https: //ourworldindata.org/agricultural-production).

The global average maize yield was approximately 2 tons per hectare in 1961, it has increased nearly threefold since then to approximately 6 tons per hectare in recent years (Figure 2) (Csorba, 2024). The current global average maize yield is 5640 kg ha^{-1} as documented by Zhang et al. (2023c), which speaks volumes for ongoing advances in breeding, agronomic management, and technology application.

Table 1. Maize production in the world from 1961 to 2023 (**Source:** Our World in Data, Accessed on 11 May 2025. https: //ourworldindata.org/agricultural-production).

Country	Year	Maize Production (tonnes)
United States	1961	91388000
	2023	389694460
China	1961	18000000
	2023	288842300
Brazil	1961	9036237
	2023	131950250
France	1961	2480000
	2023	12834600
Romania	1961	5739600
	2023	8744000
Hungary	1961	2736903
	2023	6242410

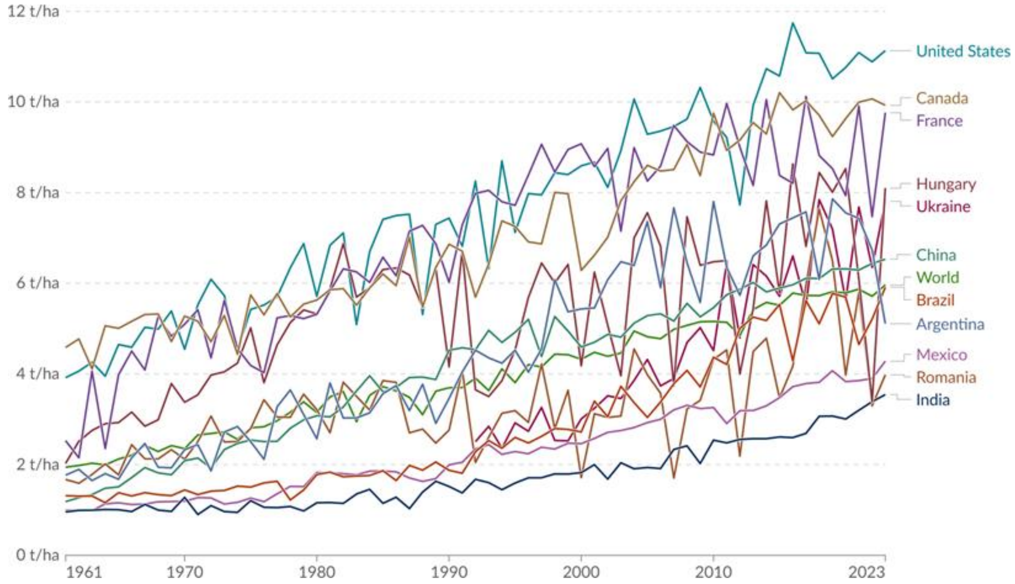

Figure 2. Maize yields from 1961 to 2023 (**Source:** Our World in Data, Accessed on 11 May 2025. https: //ourworldindata.org/agricultural-production).

Maize has long been a major crop in Hungarian agriculture. Hybrid breeding began in the 1930s (Sharif and Ansari, 2013) and the first Hungarian hybrid, Martonvásári Mv 5, was registered in 1953 and widely produced across Europe (Marton, 2013). Developed under the leadership of the breeder Endre Papp, it was considered one of the greatest achievements of Hungarian plant breeding in history. From the 1960's, hybrid adoption raised yields above 2.5 t ha^{-1} and reaching 6 t ha^{-1} by the 1980's (Oros, 2013), supported by fertilizer use, weed control and mechanisation. However, excessive inorganic fertilizer use became common due to limited environmental awareness (Marton et al., 2020). After political changes, fertilizer subsidies ended and production declined in the early 1990s, followed by gradual recovery and regaining competitiveness in European markets. Since 1990, maize average yields have fluctuated considerably due to drought (Figure 3), though better seeds, precision farming and climate adaptation have contributed to recent gains.

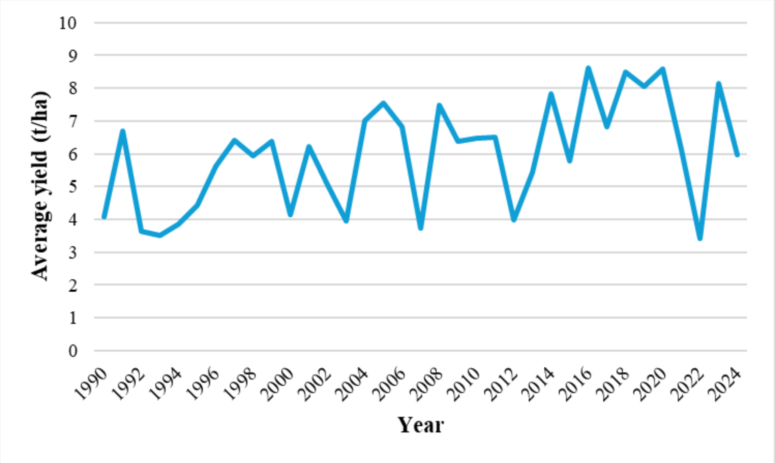

Figure 3. Average maize yield in Hungary (1990 to 2024) (**Source**:. KSH Accessed on 13 May 2025. URL https://www.ksh.hu/stadat_files/mez/en/ mez0018.html).

Being a C_4 plant, maize exhibits a special morphological feature called Kranz anatomy, which makes it well-suited to hot and dry climates (Sedelnikova et al., 2018). Its exceptional yield potential has earned it the title ’queen of cereals’ (Thakur et al., 2020), and it plays major roles in food, feed, and industry worldwide (Erenstein et al., 2022). While 80-90% of maize is used as livestock feed in developed countries (Nagy, 2006), it remains a staple food for low-income populations in developing regions (80-90%) (Horváth et al., 2021). Maize production is increasingly threatened by rising temperatures, erratic rainfall, and soil degradation. Yields may decline by 6-7% per 1°C increase in global temperature (Zhao et al., 2017; Lesk et al., 2016), while heat stress during silking and pollination can cause additional 7-23% loss (Luo et al., 2023; Rezaei et al., 2023). Intensifying droughts could further reduce yields by 10-25% by 2050, especially in rainfall-dependent regions (Buzási et al., 2021; Abebaw, 2025). Meanwhile, global food demand is projected to rise by 70% (Randive et al., 2021; Zhai et al., 2022) as the population approaches 9 billion by 2050 (Godfray et al., 2010; Del Borghi et al., 2022), and dietary shifts towards higher caloric and feed requirements (Farooq et al., 2023). Soil degradation, on the other hand, is affecting 20-33% of cropland which further limits productivity (Nachshon, 2018; DeLong et al., 2015; Smith et al., 2024).

To boost maize yields, it is essential to understand nutrient uptake and dry-matter accumulation during critical growth stages, when deficiencies can cause permanent losses (Ren et al., 2017; Rafique, 2020; Amissah et al., 2024; Du et al., 2024; Li et al., 2025). Fertilizers, including foliar applications, play a crucial role in supporting plant growth and development (Ahmad et al., 2023). Foliar feeding supplies macro- and micronutrients rapidly when soil uptake is limited, particularly during flowering and grain filling, enhancing biomass and reproductive success (Singh et al., 2013). Because leaf absorption remains active even when root activity declines, foliar fertilization is especially effective under water stress (Kannan, 2010). Similarly, efficient irrigation during tasseling and ear formation is vital, as drought at these stages can reduce yield by up to 40% (Cakir, 2004), and supplemental irrigation helps maintain pollination, grain set, and overall yield. Hybrids also differ in their capacity to remobilize nutrients to the grain during filling (Guo et al., 2018; Mi et al., 2001; Ray et al., 2020), a key trait supporting yield stability under late-season stress. Precision agriculture technologies like drones and soil sensors enable more accurate, timely input management, improving nutrient-use efficiency and reducing losses (Széles et al., 2024; Chiedu et al., 2025). Together with genetic selection for nutrient remobilization, they enhance maize yield resilience under drought and heat while supporting sustainability.

Here comes our study, which has the following objectives:

- Evaluate dry matter and nutrient accumulation dynamics in different plant parts of two maize hybrids across phenological stages, grown under field conditions.
- Determine the response of the vegetative attributes of two maize hybrids to foliar fertilization under two water regimes (irrigation in the first year and irrigation and without irrigation in the second year).
- Evaluate the effects of foliar fertilization on grain quality traits under both water regimes.
- Evaluate maize yield and yield components responses to foliar fertilization under two water regimes.
- Comparative analysis of the commonly studied parameters across two growing seasons.

2. Literature Review

2.1 The importance of maize, its origin and distribution

Maize (*Zea mays*. L), commonly known as corn, is a monoecious plant and comes from the grass family Poaceae (Gramineae), Andropogoneae tribe, and Maydeae subtribe (Barrière, 2000; García-Lara and Serna-Saldivar, 2019). Historically, maize was domesticated from the wild plant teosinte Zea mays ssp. parviglumis (hereafter parviglumis) more than 9,000 years ago in the Balsas River Valley of southwestern Mexico (Kennett et al., 2020; Erenstein et al., 2022, Dominguez et al., 2024). This domestication occurred through a series of genetic and morphological transformations that turned the branched, seed-breaking teosinte into the single-stalked, cob-like maize that is cultivated today. The origins and initial spread of maize are subjects of study and debate based on archaeological and genomic evidence, which has remained controversial. Since then, maize yield greatly increased, enabling it to become the basic food plant for the American civilizations. One of the pivotal moments in the global distribution of maize occurred after Christopher Columbus sailed to the Americas in 1492. The Columbian Exchange introduced American produce, such as maize, to Europe, Asia, and Africa, changing agricultural systems and diets around the world. In addition, maize's ability to adapt well to diverse climatic and agroecological conditions has made it a common component of agricultural systems worldwide. Its flexibility, coupled with high yields and multiple uses, means that maize is currently one of the most important cereal crops harvested worldwide.

2.2 Maize Morphology

Maize plant has a single, grooved stem composed of internodes. The nodes are where the leaves join to the stem. Each leaf has a sheath and a wide blade. The veins within the leaves are parallel, whereas the leaves themselves are positioned oppositely. The number of leaves per plant varies with variety, ranging from 10 to 15. The flowers are unisexual and are divided into male (terminal panicle) and female (ear) inflorescences, which are composed of spikelets carrying two blooms. Maize kernels consist of an endosperm, embryo, a bran or pericarp and tip cap (Figure 4). The endosperm contains the main carbohydrates. That embryo contains the parts that give rise to the next generation, while pericarp and tip cap cover the entire kernel by a thin outer layer (Du Plessis, 2003). The roots have a fasciculated structure (Kouakou et al., 2024).

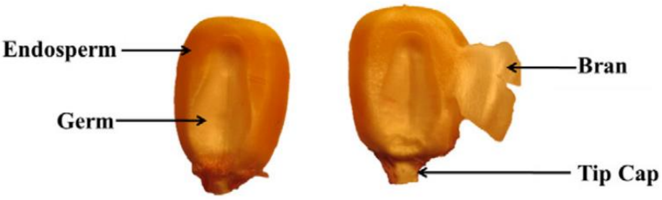

Figure 4. Maize kernel components (Macke et al., 2016).

Due to its domestication and evolutionary history, maize exhibits exceptional morphological diversity. This particular variety reflects extensive human modifications through selective breeding from teosinte and adaptation to specific needs and environments, including enhanced edibility, harvestability, and productivity. These alterations, known as ‘domestication syndrome’ (Doebley et al., 2006), of the wild form of maize have resulted in limited branching of the stem and radicalization of its female reproductive structures (Figure 5). Molecular population genetic scans and quantitative trait locus (QTL) mapping have identified multiple genomic regions associated with maize domestication. Genes that seem to be in charge of different morphological or phenological differences between maize and teosinte have been discovered through molecular analysis of QTL, including tga1, gt1, tb1, etc. (Swanson-Wagner et al., 2012). A notable change was the development of the ears and kernels of the crop, particularly the differences between its teosinte ancestor and the domesticated maize form. Unlike teosinte, which has small ears containing few kernels, domesticated maize has exposed, large ears with soft kernels that are easier to eat and process (Wang et al., 2005). The increase in accessibility of maize kernels was assumed to be due to mutations in the teosinte glume architecture 1 (tga1) gene which decreases the size and hardness of the glumes, thus allowing kernels to sit freely on the cob (Wang et al., 2005). In addition, teosinte produces multiple small ears, whereas, maize typically features one or two larger ears. This difference in prolificacy is influenced by genes like grassy tillers 1 (gt1), where a regulatory alteration caused the secondary ear buds to be suppressed in maize, making it easier to harvest (Wills et al., 2013). Besides, maize exhibits a marked difference in branching pattern compared to more highly branched teosinte. This change is associated with greater expression of the teosinte branched 1 (tb1) gene, which suppresses lateral branching, resulting in a more single-stemmed plant shape that is advantageous for cultivation and harvesting (Clark et al., 2006; Swanson-Wagner et al., 2012). The nonshattering rachis is also another important morphological adaptation in maize ears. Unlike teosinte, which has ears that break apart to scatter seeds automatically, maize possesses a rigid rachis that retains that the kernels on the cob, which increases the efficiency of harvest (Stitzer and Ross-Ibarra, 2018). The combination of these form and structure changes shows the effects of artificial selection processes on the domestication of maize, which had maize become dependent on human farming. Morphologically, maize is known to have a tall monoecious plant exhibiting separate male and female inflorescences on the same plant, and it produces grains on the sides of branches (laterals) rather than on the tops (terminals). The advances in plant breeding and molecular genetics have revealed more details of maize morphology that have helped to produce new cultivars with improved yield, stress tolerance, and adaptability (Dong et al., 2020).

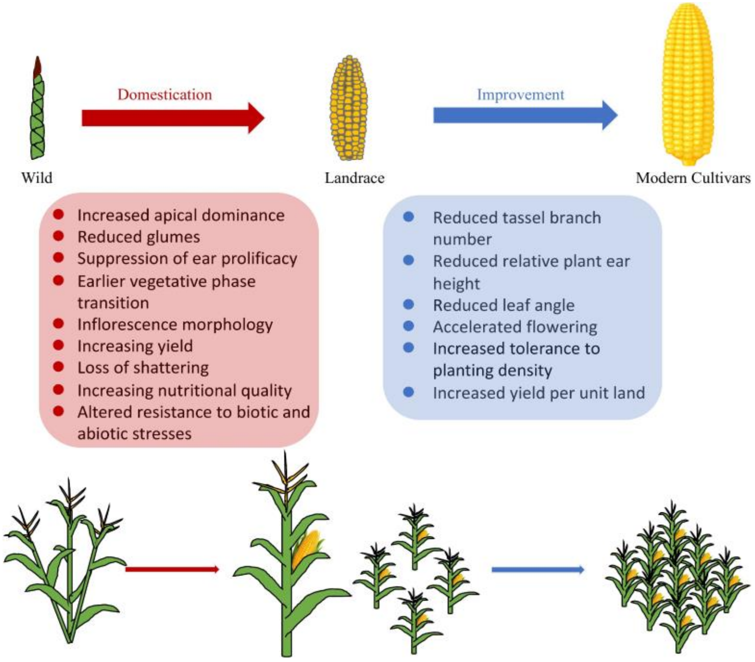

Figure 5. Main traits of maize involved in domestication and improvement (Zhang et al., 2023a).

Maize exists in several types, such as dent, flint, sweet, popcorn, flour, and waxy maize, all of which have particular features and are used differently. Maize kernels are also multicolored, ranging from white to yellow, red, and black. Sweet maize is high in sugar and is typically consumed fresh, whereas popcorn has a tough outer shell that enables it to pop. Dent maize contains high amounts of starch and is used in the feeding of livestock and various industries. Waxed maize is useful for food processing as it is predominantly made of amylopectin. These types show the selective breeding as well as the natural diversity (Guzzon et al., 2021).

2.3 Maize growth cycle

Maize growth and development combine complex processes. During the plant life cycle, different growth stages overlap, as one part of the plant develops, the other one may die. One of the key aspects of maize growth is the dynamic of dry matter, which is the accumulation and distribution of dry matter throughout the different stages of plant development (Liu et al., 2017). The dry matter accumulation is the base of yield formation (Guo et al., 2022), the analysis of its dynamic changes is critical for yield prediction (Zhu et al., 2022). Therefore, plant development deals with the progression of the plant from the vegetative phase to the reproductive phase (Table 2). The vegetative growth of a maize plant includes mainly the stem, leaves, and roots. The reproductive stage includes the flowering and fertilization processes (male flowers in the cluster and female flowers on the outer earbuds in the same plane) and the grain-filling stages (blister stage, milk stage, soft-dough, and hard-dough stages).

Table 2. Growth and development stages of maize.

Vegetative stages	Reproductive stages
VE: Emergence	R1: Silking-silks emerge from the husks
V1: First leaf collar	R2: Blister-kernels turn white and develop a blister-like structure
V2: Second leaf collar	R3: Milk-kernels turn yellow on the outside and filled with a milky liquid
V3: Third leaf collar	R4: Dough-milky fluid inside kernels thickens into a dough-like paste
Vn: nth leaf collar visible	R5: Dent- kernels begin to develop indentations
VT: Tasselling-tassel branches become prominent	R6: Physiological maturity- black layer appears, marking the end of grain development and maximum weight

Hanway (1966) identified the stages of maize growth into 10 main stages, from stage 0, at which the plant tip emerges from the soil, to stage 10, when the plant is mature. In the first half of the scale, from the emergence to the flowering stage, the different stages can be identified by counting the number of leaves that are fully developed. While the next half of the scale consists of identifying the development of the kernels on the ears. Throughout the plant's life cycle, each phase of growth needs specific conditions to support healthy development and achieve optimal yields.

2.3.1 Water requirements

Maize water requirements vary significantly throughout its growth cycle, with critical periods demanding more precise irrigation to avoid yield losses. In the initial phases of plant development (VE-V6), maize requires low to moderate water primarily to support its leaf development. However, the flowering and pollination stages (VT-R1) are considered critical periods for water availability, where a shortage in water may lead to poor pollen viability and reduced kernel set, ultimately causing significant yield losses. During the grain-filling stages (R2-R4), adequate water is necessary to ensure the size and weight of the kernel, which directly affect the overall productivity. Reaching the maturity stages (R5-R6), the plant's water requirements decline progressively. During these stages, maize is more tolerant to water stress, and irrigation is normally ceased after flowering to prevent waterlogging that may significantly affect yield.

2.3.2 Dry matter accumulation dynamics

The dry matter accumulation in maize is the process by which the plant transforms absorbed nutrients and water into organic compounds, which ultimately contributes to grain yield. The dynamic of dry matter content is connected with the loss of moisture content. Once the physiological maturity stage is reached, active metabolic processes cease. This is marked by the appearance of the black layer in the kernels, signaling that the maximum dry weight has been achieved. The distribution of dry matter among plant parts at every physiological stage is different. In the vegetative stage, from planting to tasseling, the plant is growing up and its roots are developing. In this stage, the dry matter accumulation is relatively slow, as the majority of the plant's energy is going towards developing a robust root system in order to effectively extract water and nutrients. As the root system becomes more extensive, the amount of dry matter accumulation also increases. At the later stage, between the tasseling and silking, the dry matter rate increases significantly, well as the crop nutrients and water requirements increase as the seed formation starts. The highest rate of dry accumulation occurs during this stage, as plant energy is funneled towards the developing seeds (Hanway, 1963). This stage occurs between R3 (milk stage) and R6 (physiological maturity) stages, is when dry matter begins to accumulate in the kernels (Sala et al., 2007; Byamukama et al., 2013). During the final physiological phase, called grain-filling, the maximum amount of dry matter accumulation is reached. In this particular stage, the plant stores nutrients and carbohydrates in the seeds, and the kernels mature. It is considered the most critical stage for maize yield improvement, therefore, effective management is necessary to maximize yield. Dry matter accumulation is then a critical physiological process that is essential in influencing the production and attributes of maize grains (Ning et al., 2013). The final yield is closely linked to the dynamics of dry matter accumulation, its distribution, and subsequent transport within the plant. This especially evident throughout the phase of grain-filling (Figure 6) (Ferrise et al., 2010; Bodnár et al., 2018). It has been documented by several studies that the accumulation of dry matter during post-silking stage plays a key role in determining grain yield (Liu et al., 2017; Cao et al., 2021). It has been demonstrated that the post-silking dry matter content exceeds 60% when the grain yield surpasses 18 Mg ha^{-1}, whereas it reaches only 50% when the grain yield falls below 9.0 Mg ha^{-1} (Liu et al., 2023b). Therefore, as the dry matter accumulation increases at post-silking, higher yields are achieved. The rate and distribution of dry matter accumulation during this stage determine the final maize yield. In the initial phases of plant development, the rate of accumulation of dry matter increases to reach its maximum and then slows to zero as the seed reaches its maximum weight at physiological maturity (Egli, 2017). Furthermore, the distribution of assimilates during this stage affects grain quality, including size, weight, and chemical composition. During the process of grain-filling, maize grains store around 50% of total dry matter, while the remaining 50% is accounted by the other plant organs (Lee and Tollenaar, 2007). By that, the grain attains its maximum dry matter content when the black layer becomes visible on the kernel (Carter and Poneleit, 1973), indicating physiological maturity (Daynard and Duncan, 1969). The black layer is developed underneath the testa (skin of the seed) at the base of the seed, where the cells of the conjective tissue died (Nagy, 2006).

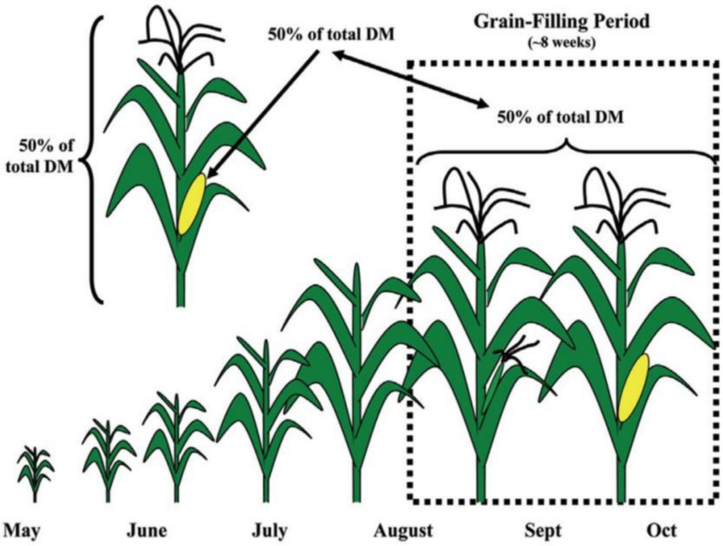

Figure 6. Pattern of dry matter accumulation throughout of growing season and distribution within a mature maize plant (Lee and Tollenaar, 2007).

2.3.3 Factors influencing the dry matter accumulation dynamics

Extensive research has shown that climatic factors exert a significant impact on the growth and productivity of maize (Asare et al., 2011; Chen et al., 2011; Edreira et al., 2011). Temperature and radiation are fundamental factors that drive biomass accumulation and crop yield by influencing essential physiological processes like carbon fixation and respiratory metabolism (Holzkämper and Fuhrer, 2013). The optimum temperature for maize growth ranges from 22 °C to 30 °C, where the photosynthesis rate is maximum (Ayub et al., 2020). Low temperatures decrease the biomass and leaf area because of the low net assimilation rate, while high temperatures decrease dry matter accumulation by reducing the duration of crop development (Zhou et al., 2016). However, due to high temperatures, the duration and rate of grain filling can be altered, which in turn affects the harvested yield (Wilhelm et al., 1999; Dupont and Altenbach, 2003). In their study, Cai et al. (2022) found that from tasseling to maturity, the accumulation of dry matter was sensitive to drought. This was due to the reduction in dry biomass of arieal parts to different extents, which highlighted the differences between crops planted on different dates. Cai et al. (2023) found that drought stress changed dry matter partitioning within maize plants, as it significantly increased the allocation in vegetative organs while reducing the dry matter partitioning to the ear and kernels, thereby lowering the harvest index (HI). Water stress is a critical element influencing dry matter, which in turn impacts growth and the ultimate yield. It adversely affects maize photosynthesis activity, canopy development, and biomass production during specific growth stages (Song et al., 2019). These sensitive periods often coincide with critical phases of growth for the crop. According to Song et al. (2019), water stress had a considerable impact on maize morphological development and physiological processes, resulting in decrease in LAI and biomass, which was linked to reduced intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE). They also observed that the deterious effect of water stress persisted throughout the reproductive phase, resulting in delayed silking and maturity dates and consequently a reduction in unit kernel weight and yield. The study revealed that maize subjected to intense and protracted water stress, particularly during the seedling phase, exhibited structural damage to the photosynthetic membrane, leading to a reduction in chlorophyll content and consequently RUE. Bouazzama and Xanthoulis (2012) reported that dry matter yields dropped from over 16 t/ha under full irrigation to as low as 3.9 t/ha under severe water stress conditions. They suggested that the reduction was associated to the inhibited plant height growth, accelerated leaf senescence rate, and reduced leaf area index, which altogether limit photosynthetic and biomass productivity. Moreover, the uneven distribution of solar radiation is a limiting factor affecting the plant yield. The study by Yang et al. (2021) found that both canopy light interception and photosynthetic rates declined as solar radiation decreased. At silking, aboveground dry weight decreased by 11.1%, and by 21% at maturity. In particular, the dry weight of vegetative and reproductive tissues dropped by 9.8% and 20.9% at silking, and by 12.1% and 25.5% at maturity, respectively. Another factor that may influence the dry matter is seeding rate. Studies (Tompkins et al., 1991a; Tompkins et al.,1991b; Arduini et al., 2006) revealed that higher seeding rates led to greater accumulation of dry matter before anthesis. Appropriate planting density can optimize sunlight capture and reduce competition among plants, which may result in a significant dry matter accumulation. Hou et al. (2020) demonstrated that an increase in plant population led to an improvement in grain yield. This enhancement can be attributed to the increased the interception of light, photosynthesis, and effective use of light due the increased plant density. This, in turn, leads to the augmented aboveground dry biomass and subsequently higher grain yield (Maddonni et al., 2001; Xu et al., 2017; Bernhard and Below, 2020). It was demonstrated by Allison (1969) that the amount of grain dry matter accumulated post-flowering increased from 73% at a population density of 23 000 ha^{-1} to 82% at densities between 60 000 and 74 000 ha^{-1}. Also, it was revealed by Wei et al. (2019) that at both tasseling and harvest stage the maize dry matter accumulation was significantly influenced by plant density.

2.3.4 Nutrients accumulation dynamics

During the growing season, the demand for and uptake of nutrients by maize shift dynamically in association with key vegetative and reproductive growth stages. The plant's needs are reflected in its metabolism and the allocation of nutrients to different tissues at different stages, which determines the concentration, accumulation and absorption of each nutrient. Maize predominantly accumulates nitrogen, phosphorus and potassium in its early phases of growth. These macronutrients are necessary for leaf pigmentation and expansion, root and stem development, and overall plant vigor. For instance, nitrogen, supports chlorophyll synthesis and photosynthesis, contributing substantially to leaf pigmentation, and grain yield formation (Asare et al., 2023; PDA, 2024). Phosphorus, the second most frequent limiting macronutrient for plant growth (Schachtman et al., 1998; Isidra-Arellano et al., 2021), is readily remobilized from older to younger tissues due to its mobility within the plant

(Raghothama and Karthikeyan, 2005) and plays crucial roles in root, leaves and stem development (Masood et al., 2011; Liaqat et al., 2018), metabolism (structural component in nucleic acids, coenzymes, phosphoproteins, and phospholipids) (Grant et al., 2001), cellular energy transfer (Maathuis, 2009), and processes like respiration and photosynthesis (Raghothama and Karthikeyan, 2005). However, phosphorus deficiency, during early plant growth, can lead to stunted growth, while it has a smaller impact later in the season (Grant et al., 2001). According to Görlach et al. (2021), decreased plant height, reduction in tillering, restricted seed formation, reduced leaf area, and premature senescence of leaves are among the main P limitation symptoms. Potassium, another mobile nutrient, regulates osmoregulation, ion balance, enzyme activation, and transport of photosynthates (Sadiq et al., 2017; Zhang et al., 2023b). In addition to its essential role in overall plant growth, development, and sustainable yield (Bukhsh et al., 2012), potassium enhances stalk bending strength, which is vital for maintaining plant structural integrity and resistance to lodging Xu et al. (2018). Calcium, one of the macronutrients, is primarily absorbed in the leaves, where it supports cell wall stability and membrane integrity (Kirkby and Pilbeam, 1984), as well as cell division and elongation (Pathak et al., 2020) , and leaf development (Bromley, 2010). In contrast, magnesium accumulates mainly in the stalk due to its central role in chlorophyll structure and ATP-dependent metabolic processes (Taiz and Zeiger, 2002). It also supports enzyme functions essential for photosynthesis and protein biosynthesis (Senbayram et al., 2015). Sulfur concentrations can be found in highest levels in the leaves because it is essential for amino acid and protein synthesis (methionine and cysteine) (Rahman et al., 2011), as well as for the synthesis of antioxidant defence compounds such as glutathione (Sutar et al., 2017; Li et al., 2020; Narayan et al., 2022). During reproductive development, sulfur concentrations in ear components increase, reflecting its involvement in chlorophyll formation, flowering and seed development. Micronutrient accumulation follows similarly distinct patterns. Leaves accumulate the highest concentrations of iron and manganese due to their roles in photosynthesis and redox metabolism (Millaleo et al., 2010). However, excessive iron can be toxic, causing oxidative stress (Rout and Sahoo, 2015; Li et al., 2018; Farid et al., 2023). Copper also primarily accumulates in leaves due to its involvement in photosynthesis and antioxidant defence (Barbosa et al., 2013), but becomes toxic at elevated levels due to its limited mobility (Bouazizi et al., 2010). Whereas, the stalk may accumulate higher zinc concentrations, reflecting its involvement in enzyme activation, cell wall structure and protein synthesis. Boron, on the other hand, exhibits a unique pattern, where its low mobility results in its early accumulation in vegetative tissues, particularly leaves (Bayar et al., 2024). Boron deficiency during the early stages can hinder root and stalk development, cause leaf deformities and reduce overall vigour. However, demand for boron increases again during grain filling, as it plays a critical role in pollen tube formation and seed development (Devi et al., 2016; Kaur and Nelson, 2015). As the maize plant transitions to the reproductive stage, the allocation of nutrients shifts towards the development of the ears and kernels and the demand for nutrients intensifies. Therefore, high amount of these essential nutrients is required for garin development. Lastly, frrom grain filling to physiological maturity, the accumulation of dry matter and nutrients reaches its highest levels.

2.4 Climatic and soil requirements

According to FAO (2025), maize can be grown in temperate to tropical environments with average daily temperatures above 15°C and no frost. However, elevated temperature can directly affect the crop growth rate and development (Srivastava et al., 2021). Maize, often known as the ”queen of cereals”, can be cultivated throughout the year and is cultivated most efficiently thanks to its highest yield potential as well owing to its adaptability to different soils and climatic conditions (Srivastava et al., 2021). Depending on climatic conditions, the maize plant requires 500-800 mm as the optimal range for yield (Bouazzama and Xanthoulis., 2012; FAO, 2025), which makes it a relatively large water consumer. This makes the maize crop highly sensitive to water stress or drought (Pandey et al., 2000; Cakir, 2004), especially during the tasseling, silking, and pollination stages (Taghvaeian et al., 2013). Temperature is another key climatic factor influencing maize performance. The lower the temperature, the longer the time duration the plant needs to intercept radiation (Gowda et al., 2013). The concept of heat unit, according to these authors, consists of the amount of heat required for the completion of each stage of its ontogeny. Horváth et al. (2021), Nandini and Sridhara (2019), and Ahmed and Saikia (2020) reported that heat unit has a direct influence on crop productivity for yield and quality, particularly during the critical period of maize hybrid development, in which a specific amount of thermal units is required to attain each stage. The optimal temperature for the crop to achieve proper germination and growth is between 21 and 32°C, with substantial moisture supply (Jaidka et al., 2019). Although, throughout the vegetation period, the thermal requirement is relatively high, and the optimum temperature is between 28 and 30ºC (Cofas, 2018). Therefore, lower temperatures during this period may cause plant growth to cease, yellowing or whitening of the plant. Although additional factors to water stress, temperature, light, and humidity, soil nutrients is one of the major limiting factors. Maize cultivation is adaptable to diverse soil textures, including loamy sand and clay loam, particularly those enriched with good organic material, possessing strong moisture retention and a neutral pH (Parihar et al., 2011). As stated in Nagy (2006), water shortages and nutrient limitations can affect maize, particularly during specific physiological phases, which are critical to crop healthy development.

2.4.1 Irrigation

Variations in climatic conditions could potentially alter the process of growth and maturation of maize, ultimately impacting its yield. The lack of available water in soil, for instance, may limit the activity of enzymes involved in metabolic plant processes, causing a reduction in plant leaf area and biomass, as well as a deacrease in the photosynthetic rate, which is the consequence of a reduction in the chlorophyll content of the leaves. Consequently, this ultimately leads in a loss of yield in maize (Nesmith and Ritchie, 1992; Chaves et al., 2002; Liu et al., 2018; Zhang et al., 2018; Laskari et al., 2022). Thus, the projected escalation in water scarcity and prevalence of extreme weather events may engender a decline in yields, accentuated yield variability, and a shrinkage in cultivable areas suitable for traditional crops (Olesen and Bindi, 2002). Nagy (2010) underscored the role of irrigation in mitigating nearly 5% of the negative consequences caused by drought. In drought affected environments, throughout the vegetative period, crop growth rate might be reduced, the vegetative growth stage can be prolonged, roots can be redirected, and maize carbohydrate distribution can be altered (Wang et al., 2019). Therefore, noticeable effects of water stress on maize include stunted growth, delayed maturation, decreased biomass, and lower grain yield (Farré and Faci, 2009). Dioudis et al. (2009) also highlighted the importance of irrigation, especially after the tasseling stage until reaching maturation. Rogers (1994) recommends maintaining the soil moisture above 50% of field water capacity during these stages, as they are critical to water stress. However, it has been demonstrated that maize exhibited a certain level of tolerance to water stress in the initial vegetative phases and the subsequent grain-filling phases, as these phases exhibit minimal water requirements (Kang et al., 2000). Consequently, maintaining consistent irrigation during the flowering stage can lead to high maize yields, even when soil moisture is limited during the vegetative growth and grain-filling stages (Igbadun et al., 2007).

It has been found that the flowering period is the most sensitive to water deficit and most susceptible to drought stress (Otegui et al., 1995). The prevalence of severe drought may result in the production of barren ears (Aslam et al., 2015). In addition, the resulting damages include, delayed inflorescence development, asynchronous flowering, blasting of the tassel, reduced pollen fertility and viability, reduced pistil receptivity, and aborted embryos (Spitkó et al., 2014). Moreover, research has revealed that limited water availability leads to a marked decline in maize dry matter by the maturity stage (Karam et al., 2003; Bozkurt et al., 2011). Moreover, the potential of irrigation is not limited to increasing yield but also in improving the nutritional quality of maize grain, including protein, oil, starch content, and mineral composition (Kresoví et al., 2018). Therefore, irrigation is vital for sustaining maize production under climate change scenarios. To tackle these limitations management strategies have to be implemented, seeking to mitigate the potential adverse impacts on agricultural productivity. Therefore, it is necessary to consider which plant species may require less water or tolerate low soil moisture (Al Rawi et al., 2021). For example, where drought events conquer such regions, the recourse to the use of irrigation seems to be necessary to increase crop productivity. Management practices (tillage, conservation tillage, deficit irrigation, etc) played and still play a significant role in addressing many challenges we face to this day. Adding to that, the selection of the appropriate high-performance seed variety adapted to different environmental conditions, such as drought, is the key to maintaining or improving higher maize yields. Furthermore, numerous efforts were devoted by scientists and breeders to this specific research topic, aiming to evaluate the performance, stability and adaptability (Bojtor et al., 2021; Shojaei et al., 2022) and stress resistance (Mostafavi et al., 2013) of new breeding genotypes.

2.4.2 Fertilization

Maize is considered a heavy feeder that displays particular nutrient needs that differ according to the specific phenological stage of its growth cycle. Maize productivity and physiological progression are contingent upon the availability of key macro and micronutrients. As Nagy (2006) highlighted, maize displays sensitivity to nutrient availability, notably during pivotal physiological stages that are essential for robust crop croissance. The nutrient requirements of the plant are determined by its metabolic processes and the way in which nutrients are distributed between tissues at a given stage of development. Throughout its development, maize undergoes shifts in nutrient uptake and requirements (Vágó et al., 2014), that are closely associated with key stages of both vegetative and reproductive growth (Stewart et al., 2021). The aforementioned researchers stated that, nutrient acquisition typically reaches its maximum between V10 and V14, after which it stabilizes around the VT/R stages, resulting in a sigmoid curve for the seasonal nutrient accumulation. In the growth phase, as biomass accumulation increases, the need for nutrients and the rate of nutrient uptake both rise. At this point, the plant shows an increased ability to assimilate substantial quantities of nitrogen, phosphorus, potassium, and other essential minerals. Consequently, this phase is considered pivotal, as deficiencies at this point can markedly impact the overall yield. Subsequently, the formation of maize cobs commences during the reproductive stage, constituting the principal yield factors and being significantly impacted by the availability of nutrients. Consequently, a substantial intake of key nutrients is necessary to support optimal grain formation. During the grain filling and maturation phases, maize stores significant quantity of mineral nutrients. Once physiological maturity is reached, dry matter and vital elements deposition is finalized. Determining the plant's nutrient needs in relation to its phenological development to formulate an effective nutrient management strategy, particularly for high-yielding modern cultivars (Cavalcante et al., 2018).

Among agrotechnical factors, fertilization can drastically modify the yield of maize. Over the years, it has been considered the most readily available tool used to enhance yield potential and increase profits for farmers. Studies reveal that proper fertilization maximizes the yield potential and improves grain quality, including nutritional value (Sánchez-Rodríguez et al., 2021, Yang et al., 2009). Furthermore, appropriate fertilization has been demonstrated to strengthen the resilience of plants to biotic and abiotic stresses, thereby contributing to a more robust crop systems. Specific fertilization strategies have been demonstrated to substantially augment tolerance to environmental and biological challenges. For instance, the application of silicon (Si) has been demonstrated to enhance maize resilience to salinity by improving ion balance, photosynthetic efficiency, and antioxidant defense systems (Ullah et al., 2025). Additionally, zinc (Zn) and silicon (Si) fertilization have been shown to enhance chlorophyll synthesis, enzymatic activity, and yield traits, particularly under conditions of water limitation (Idrees et al., 2024). Széles et al. (2013) carried out an investigation to asses the impact of different nitrogen levels (0-150 kg ha^{-1}) on crop yield in years with both high and low precipitation. The maximum yield was established at 60 kg ha^{-1}N, both in wet and dry years. The findings of the study demonstrated that there was a mean increase in yield of 1.34 t ha^{-1} in dry crop years, while this increase was more marked in wet crop years (3.27 t ha^{-1}). Kith et al. (2019) conducted a study to ascertain the correlation between soil fertility and the yield of maize of different hybrids, categorised by maturity as either early or medium. The findings of the study demonstrated that local maize hybrids exhibited differential responses to varying soil chemical compositions. The maize hybrids demonstrated an effective utilisation of low zinc levels, while a substantial variation was observed in nitrogen levels, resulting in a high yield. Szabó et al. (2022) examined the influence of different nitrogen applications on maize hybrids productivity. They found that nitrogen fertilization significantly improved emergence by enhancing nutrient availability for germination. The third day post-sowing was identified as a critical point, having a pronounced effect on yield related traits and quality indicators, including moisture, protein, oil, and starch concentrations. Among the hybrids tested, FAO 420-440 demonstrated the highest percentage of emergence, thereby contributing to enhanced yield stability under varying nitrogen conditions. In their study, Liu et al. (2020) investigated the impact of zinc fertilization on maize cultivated in zinc-deficient soils, with a particular emphasis on pollen fertility and kernel formation in the apical (inferior) section of the ear. Zinc application significantly improved pollen viability during tasseling and boosted both the kernel count and weight in the apical section. This led to an increase in maize production of 4.2-16.7%. The study also identified critical shoot zinc concentrations of 31.2 mg kg^{-1} for high pollen viability and 35.6 mg kg^{-1} for maximizing inferior grain development, highlighting zinc's key role in improving maize productivity under deficiency conditions. Meena et al. (2013) demonstrated in their study that maize performance was significantly enhanced by fertilization. The maximum grain yield recorded was 4.3 Mg ha^{-1}, attained through the application of 150 kg N ha^{-1} in combination with 5 t ha^{-1} farmyard manure and Azotobacter inoculation. The treatment also resulted in the greatest nutrient uptake of nitrogen, phosphorus, and potassium and significantly improved grain protein content. Chipomho et al. (2020) conducted a study to evaluate the impact of 6 years of continuous soil nutrient amendments application on maize productivity. The amendments employed, comprised strategically combined NPK fertiliser, cattle manure, and lime. The study's findings revealed a strong correlation between maize yield and the soil organic carbon content (SOC). Average maize grain yields during this period were 1.31 Mg ha^{-1} at low SOC levels, 2.47 Mg ha^{-1} at medium SOC, and 2.75 Mg ha^{-1} at high SOC. It is evident that an augmentation in the content of soil organic carbon has been demonstrated to engender an escalation in the yield of maize. Furthermore, it was determined that the combined application of manure and NPK fertilizer led to a significant yield enhancements, reaching 1.5 Mg ha^{-1}, with yields further increasing to 2.47 and 2.75 Mg

ha^{-1} under moderate and elevated soil organic carbon levels, respectively. The findings of this study demonstrated that in soils with low SOC content, the greatest increases in maize yield are observed when organic and mineral fertilizers are used in combination. In line with the observations made by Sárvári and Pepó (2014), the effective use of fertilizers depend on various agrotechnical and ecological factors, including, but not limited to, soil nutrient levels in nitrogen, phosphorus, and potassium, prevailing weather conditions, water resource availability, and the capacity for soil moisture retention. The aforementioned considerations are further compounded by biological factors, such as the genotype of the particular organism in question. The study revealed that the multicultural crop rotation, involving peas, wheat and maize, contributed to maize yield increase of up to 1.31 t ha^{-1}, whereas the two-crop rotation system of wheat and maize, led to a 1.58 t ha^{-1} yield improvement, relative to the 7.39 t ha^{-1} yield from maize monoculture observed in a long-term field trial on loamy soil. The study demonstrated the significance of employing hybrid-specific technology, encompassing fertilization and planting methodologies, in the context of maize production.

2.5 Maize quality traits

The cereal crop (*Zea mays* L.) is a vital staple that contributes significantly to global food security owing to its high adaptability and nutritional value. The protein, starch, oil, and moisture content found in maize indicate the quality of maize and its contribution to food security. Maize is composed primarly of carbohydrates, with starch making up rouphly 72% of its content. It also contains around 10% protein and 4% fat, contributing to an energy yield of approximately 365 kcal per 100 grams (Nuss and Tanumihardjo, 2010; Kumar et al., 2020). Furthermore, in addition to fiber, maize provides a variety of essential B vitamins and minerals, however, it lacks certain nutrients, such as B_{12} and C vitamins. Moreover, maize is regarded as a limited source of calcium, iron, and folate. Absorption of iron, particularly the non-heme form, from maize can be hindered by certain dietary components or foods, including vegetables, tea (oxalates), coffee (polyphenols), eggs (phospholipids), and milk (calcium) (Ranum et al., 2014). The protein content in maize plays a crucial role in human nutrition, especially in maintaining health standards in regions where maize serves as the primary staple food. The nutritional value of this protein is primarly determined by the levels of essential amino acids, such as tryptophan and lysine (Sethi et al., 2023). Quality Protein Maize (QPM) has been developed to enhance these amino acids, nearly doubling lysine and tryptophan levels compared to conventional varieties (Bharti et al., 2020). Starch constitutes the primary component of the maize kernel. It is a critical quality trait that influences its use in food products and industrial applications (Arendt and Zannini, 2014). The correlation between starch content and tryptophan content is negative, thus indicating that there is a trade-off between protein quality and starch levels (Sethi et al., 2023). In a maize kernel, 85% of the oil content is located in the embryo (Yang et al., 2013). As has been extensively documented within research studies, there appears to be a negative correlation between the levels of grain oil and starch (Yang et al., 2013; Ndlovu et al., 2024). Maize moisture content plays a fundamental role in determining its preservation, longevity, and overall quality. At harvest, seed moisture content is subject to the influence of two factors: firstly, the moisture content at physiological maturity and secondly, the extent of seed dehydration after maturity. High moisture content at harvest can result in a decline in quality and an increase in the cost of postharvest drying, which in turn can lead to increased production costs for growers (Liu et al., 2022). Optimal moisture levels (below 13%) must be maintained during storage to ensure safe handling and minimize post-harvest losses, thus facilitating stabilization of the food supply (Owusu-Sekyere et al., 2021). Furthermore, the moisture content exerts a significant influence on the germination potential of maize seeds, a critical factor in preserving seed quality and maintaining high agricultural productivity (Awopegba and Matthew, 2023).

2.6 Precision technology in maize production

Precision farming is considered one of the agricultural revolutions and it involves several aspects of remote sensing, plant protection, precision planting, precision fertilizer placement, precision irrigation and yield monitoring. Among these technologies, precision nutrient delivery, particularly foliar fertilization, has shown significant potential for enhancing crop productivity. For instance, a russian field trial found that the foliar spray with a zinc-based fertilizer at the 5 to 8-leaf stage increased the green mass yield of the hybrid Mashuk 220 MV by 5.2 and 6.0 t/ha (15.1 and 17.4%) and of the hybrid Mashuk 355 MV by 7.7 and 6.8 t/ha (23.2 and 20.5%). The grain yield was also increased by 0.59 and 0.63 t/ha (9.2 and 9.9%) and 0.83 and 0.74 t/ha (12.9 and 11.5%), respectively (Bagrintseva et al., 2024). The efficiency of foliar fertilization in promoting crop yield and quality under environmental stress has undergone meta-analysis evaluation. Based on this analysis, foliar application of mineral nutrients can increase yield by 15-19% and quality characteristics by 9-29% under salinity and drought stresses (Ishfaq et al., 2022). Furthermore, precision irrigation technologies such as drip irrigation systems offer an effective way to deliver uniform water distribution across entire field areas, including hard to reach places such as corners and plots of irregular shape, where traditional irrigation methods often prove ineffective (Illés et al., 2022). Field experiments revealed that drip irrigation systems reduced water use by nearly 24% compared to higher input levels (Bian et al., 2024), significantly improving irrigation water use efficiency and offering a more efficient practice under water-limited conditions. For example, compared with border irrigation, drip irrigation systems improved water use efficiency (WUE) and irrigation water use efficiency (IWUE) increased by 53.77% and 57.89% compared with border irrigation (Liu et al., 2023a).

To achieve high productivity and stable production, it is essential to select a hybrid that is optimally suited to specific environmental conditions and stress patterns. New drought-resistant maize hybrids were discovered to produce greater quantities of grain when subjected to water and heat-related stresses in comparison to conventional varieties, enhancement ascribed to advancements in genetic and physiological characteristics that promote resilience to stress. For instance, Su et al. (2022) demonstrated that drought-tolerant hybrids in the Texas High Plains produced 19-26% more than conventional hybrids during deficit irrigation, with enhanced water productivity and reduced yield loss through augmented water-use efficiency by 15-17% and drought tolerance. Similarly, tropical and subtropical inbred lines TZISTR1164 and CML390 were found to be drought-tolerant in the research of Dube et al. (2024) while TZISTR1190 and TZISTR1231 were high-yielding and stable across a diverse set of environments. These genotypes are valuable genetic resources for creating drought-tolerant maize hybrids with stable performance under both optimal and water-stressed conditions, which will enhance yield stability and food security in drought-stress environments. Earlier, Gaffney et al. (2015), conducted a study over a period of three years (2011-2013), carrying out on-farm, industryscale testing. The study revealed that AQUAmax hybrids yielded an average of 6.5% more under water-limited conditions and 1.9% more under favorable growing conditions in the US Corn Belt. Tarekegne et al. (2024) reported significant genetic gains in grain yield of early maturation maize hybrids developed by CIMMYT, evaluated in 68 environments in eastern and southern Africa under stressed (including drought) and non-stressed conditions. More recently, Elmyhun et al. (2024), in their study, identified HB18, HB41, HB91, and HB95 as high-yielding hybrids under both managed drought with reduced temperature stress (MDRTS) and combined drought and heat stress (CDHS), reflecting their high tolerance to multiple stresses. They observed positive genotypic and phenotypic correlations for grain yield under these environments, suggesting the presence of common genetic mechanisms for adaptation to stresses.

As both hybrid tolerance and input efficiency rely on the timely detection of physiological changes, vegetation indices are essential for monitoring plant performance. Normalised difference vegetative index (NDVI) is a widely used indicator for plant health and biomass and has shown a good relationship with nitrogen status in maize plant (Rhezali and Lahlali, 2017). Normalised Difference Vegetation Index (NDVI) values clearly show plant development, health status, and biomass production (Nagy et al., 2020), The vegetation index reflects the greenness of the plant canopy and photosynthetic activity. It greatly increases the efficiency of maize production by allowing for real-time spatial management of crops. In addition to NDVI, there are other remote indicators that measure biomass and canopy activity, which are reliable indicators of crop growth, nutrient status, and vigor. The Soil Plant Analysis Development (SPAD) method is among them, and is a measure of chlorophyll content, that is most popular as it is user-friendly and non-destructive and is essential for photosynthesis and overall plant growth. Another important indicator for assessing maize growth and development is the Leaf Area Index (LAI) that reflects the canopy's capacity for light interception and photosynthesis. Monitoring changes in LAI values, indicate the variations in the growth stage and overall crop development. Moreover, foliar nutrient application is recognized as a reliable and eco-friendly approach to crop production, playing a pivotal role in mitigating harmful effects to soil properties and the surrounding environment (Sultonov et al., 2025). Foliar feeding is becoming a widely accepted agronomic practice to mitigate the likelihood of specific nutrient deficiencies and protect crops from unpredictable impacts of adverse weather throughout their growth cycle (Fernandez et al., 2013; Zargar et al., 2019). This technique has been utilised for a considerable duration. Numerous research studies have employed diverse fertilizers on various crops for a variety of research objectives including maize. In the context of prevailing circumstances, foliar fertilisation has demonstrated to be highly effective method of enhancing crop yield while minimizing environmental concerns. Drip irrigation significantly increases the dry matter and nutrient content in maize plants. In addition to enhancing water use efficiency, it has been found to reduce fertiliser leaching and soil salinisation (Yang et al., 2023), thereby increasing the crop's nutrient uptake and utilisation.

3. Materials and Methods

3.1 Description of the experiment area

The experimental field trials were carried out for two consecutive years (2022 and 2023) at the Látókép Plant Production Experimental Site of the University of Debrecen, situated west of Debrecen, Hungary (47°33’N, 21°26’E) (Figure 7). Both primary and secondary soil preparations were performed. Prior to sowing time, soil samples were collected and analyzed in the laboratory to determine their physiochemical characteristics. The experimental setup was conducted on chernozem soil, characterized by the physical and chemical attributes outlined in Table 3.

Figure 7. Maize experimental site (Látókép-Debrecen).

Table 3. Physical and chemical properties of the experiments soil (2022).

pH (KCl 1:2.5)	5.59
Arany’s Plasticity Index (KA)	38.47
Total salt (m/m%)	<0.02
$CaCO_3$ (m/m%)	<0.1
Humus (m/m%)	2.25
Nnitrite+nitrate (m/m%)	1.98
Magnesium (mg/kg)	344.50
Sulfur (mg/kg)	4.75
Potassium oxide (mg/kg)	321.18
Sodium (mg/kg)	10.10
Phosphorus pentoxide (mg/kg)	200.89
Copper (mg/kg)	2.17
Manganese (mg/kg)	240.60
Zinc (mg/kg)	0.57

3.2 Climatic conditions

Daily data on precipitation, temperatures, and cumulative heat units were recorded by the meteorological station located at the Látókép research site. According to the collected data, the year 2022 marked drought conditions (Figure 8). Throughout the growing season, notable temperature anomalies were recorded, with June being 2.9°C above average, July 2.1°C, and August 2.7°C, indicating unusually high temperatures combined with limited rainfall. During these three months, total rainfall amounted to only 56.6 mm, leading to a severe drought stress. Consequently, these environmental conditions hindered optimal maize growth. A marked shift in climatic patterns occured in September, bringing heavy rainfall (totaling 152 mm), which subsequently delayed the harvest until October. Conversly, the meteorological conditions in 2023 exhibited a favorable tendencies for the cultivation of maize. The general weather conditions were marked by mild temperatures with no extreme heat. During the growing season of 2023, precipitation was average. However, half of the precipitation fell during May and July. Nevertheless, no substantial water stress has been witnessed, that could be due to stored water in the deeper soil layers and the optimal temperature conditions.

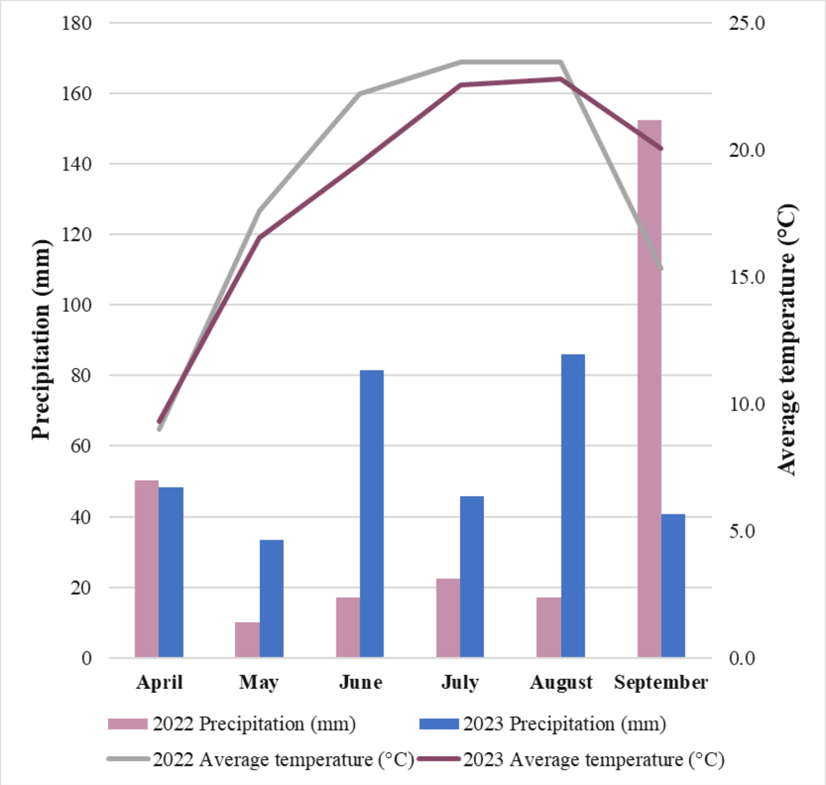

Figure 8. Weather conditions in 2022 and 2023 (Látókép-Debrecen).

3.3 Experimental design

The experiments were conducted using a randomised split-plot design. In the first cropping season of 2022, the trial consisted of two plots, one for each hybrid grown under irrigated conditions. Each plot was divided into three rows, with the control and spray-treated plots separated by an empty row for samplings. Fornad (FAO 420) and Mv 352 (FAO 350) maize hybrids, both characterized by mid-maturity and commonly cultivated in high-yielding regions of Hungary, were selected as test crops. Fornad hybrid is It is known for its strong performance in grain production, as well as for its good drought tolerance and standability, while Mv 352 is highly valued for its ability to produce consistent yields in different environmental conditions and for drying quickly.

Prior to sowing, soil preparation in 2022 was performed in four steps. Fertilizer spraying at a rate of 300 kg ha^{-1} (8:24:24) carried out on 08.10.2021, ploughing being carried out on 11.10.2021 and finished on 02.03.2022 with the application of a combinator, and lastly fertilizer spraying was performed on 29.03.2022 using 500 kg ha^{-1} CAN (39%; 27-7-5). A combinator was used to prepare the seedbed. Additionally, on 10.06.2022, nutrient solutions were applied, using Megasol orange (100 kg fertilizer) NPK 3-5-40 (3.5 kg N, 5 kg P_2O_5, 40 kg K_2O), and on 12.07.2022 using Megasol orange (50 kg fertilizer) NPK 3-5-40 (1.75 kg N, 2.5 kg P_2O_5, 20 kg K_2O). Additionally, on 29.06.2022 Mospilan 300 kg ha^{-1} and Karate Zeon 5 CS insecticide were applied for plant protection. Whereas, the soil preparation in 2023 was performed in three steps, with ploughing being carried out on 17.10.2022 and finished on 02.02.2023, and fertilizer spraying performed on 17.04.2023 using 500 kg ha-1 CAN (39%; 27-7-5). A combinator was used to prepare the seedbed. Additionally, on 10.07.2023, nutrient solution was applied, using Megasol orange (25 kg fertilizer) NPK 3-5-40 (0.875 kg N, 1.25 kg P_2O_5, 10 kg K_2O).

On 26th April 2022, the hybrids were sown with a spacing of 15.6 cm between plants and 76 cm of row spacing, establishing a population density of 62 000 plants ha^{-1}. Emergence occurred on May 6th and 7th, respectively, and the harvest was completed on October 10th. The experimental design in the second cropping season of 2023 consisted of two blocks containing the same two plots similar to those in the experiment of the first cropping season but under irrigated and non-irrigated conditions. On 20th April 2023, the seeds were sown in each row with the plantings spaced 15.6 cm apart, 76 cm of row spacing and a population of 65 000 plants ha^{-1}. The emergence of the hybrids took place 13 days post-sowing (3rd of May), and they were harvested on 28th September.

3.4 Treatments

3.4.1 Irrigation

In 2022 and 2023, a precision drip irrigation system was incorporated into the experimental design. Beginning on 27 May and continuing until 11 August, it provided a total of 456.8 mm of irrigation water across 28 applications during the growing season. The amount supplied per application ranged from 13.2 to 32.5 mm, and irrigation was supplied frequently, with an interval of 1-5 days between each application. Many applications were spaced 2-3 days apart, resulting in an overall mean interval of approximately 2.8 days. In 2023, irrigation began on 18 June and continued until 10 August in the plot that received water, providing 374 mm of irrigation water across 12 applications. Irrigation followed a two-stage pattern: early-season applications supplied 44 mm each, while later applications delivered 22 mm. The interval between applications ranged from 3 to 6 days, with several occurring four to five days apart, producing an average interval of approximately 4.8 days.

3.4.2 Fertilisation

At the 8-leaf stage in 2022 and at around the 12-leaf stage in 2023 (that explains the reason we don’t have measurements regarding the treated plots at this stage), foliar fertilizers were applied to the studied hybrids on the designated rows. The fertilizers were supplied by Natur Agro Hungaria Kft, and they were applied by their professionals. The treatment consisted of a combination of 2 l ha^{-1} Natur Plasma T biostimulant, 4 l ha^{-1} Natur Active complex foliar fertilizer, 1 l ha^{-1} Zinc mono additive (120 g l^{-1}), and 1 l ha^{-1} Sulphur mono additive (91 g l^{-1}). Natur Plasma T is a biostimulant made from concentrated algae and their beneficial organic compounds. Apart from delivering vital nutrients, it also fosters plant recovery and growth. It contains vital amino acids (both essential and non-essential amino acids), vitamins, and plant growth regulators. The nutrient profile includes N, P, K, Ca, Mg, Fe, Cu, Zn, Co, Mo, B, S, Na, and C. Natur Active, is a complex foliar fertilizer, provides vital macro and micronutrients necessary for plant health. This solution contains 13 different concentrated nutrients, including:150 g l^{-1} N, 1.25 g l^{-1} P_2O_5, 37.5 g l^{-1} K_2O, 5g l^{-1} MgO, 5g l^{-1} S, 0.625 g l^{-1} CaO, 3.75 g l^{-1} Fe, 2.5 g l^{-1} Mn, 1.5 g l^{-1} Cu, 1.875 g l^{-1} Zn, 2.5 g l^{-1} B, 0.125 g l^{-1} Mo, 0.0625 g l^{-1} Co. According to the manufacturer’s guidelines for the commercial foliar fertilizers used, these products enhance maize plant’s response to abiotic stress, improve its resistance to diseases and pests, and promote overall growth and yield.

3.5 Data collection

During every growing season, we collected all the necessary data for our study including soil, meteorological data and heat units accumulation data. Besides to this, few other parameters regarding plant growth and development and grain attributes were also measured.

3.5.1 Dry matter

The measurements of dry matter was undertaken in accordance with the classification system of phenological stages proposed by Hanway (Hanway, 1963). The researcher defined the pre-silking developmental stages based on leaf number, while the subsequent stages were determined according to grain development, dividing the maize growing cycle into 11 distinct stages.

In the 2022 growing season, the nutrient composition of the hybrids was assessed at six phenological stages: V6, V12, R1 (Silking), R2 (Blister), R4 (Dough), and R6 (Maturity). At each of these stages, four plants were selected at random from each hybrid. In 2023, a similar approach was followed, with four were chosen randomly from irrigated and non-irrigated plots at four stages (V12, R1, R4, and R6).

The collected plants were then separated into different parts: leaves, stalk with tassel, ear with silk, cob, kernels, and husk. The plant material was transferred in paper bags and dried in an oven at 60°C until a constant weight was achieved, with drying times ranging from 72 to 120 hours, depending on the growth stage. After drying, the samples were weighed to determine their dry matter content (DM). Subsequently, the samples were sent to an accredited laboratory for nutrient concentrations analysis. The pretreated (dried, grinded) samples were analysed as the following:

- N-content was measured with Kjeldahl method according to the MSZ-08-1783-6:1983 Hungarian standard: 1 g of the samples were measured out into N-free paper and were hot digested in H_2SO_4-H_2O_2 using selenium as catalysator (VWR International). The NH_4-content of the residue was distilled in automated distillatory equipment (VELP UDK 149) into 4 |m/m|% boric acid and was titrated with 0.2 N H_2SO_4 using TITROLINE 5000 automated titrator (SI Analytics).

- The rest of the nutrient: 0.5 g of the prepared average sample was weighed, and 5 ml of distilled cc. HNO_3 along with 3 ml of 30% H_2O_2 were added. Then, the samples were destructed using an Ethos Plus Milestone microwave destructor and in accordance with Application Note 076, followed by measurements in ICAM 7000 spectrophotometer, measuring the wavelength spectral line of the plasma light emission characteristic of each element.

3.5.2 Growth parameters

In 2022, we recorded the values of the Normalized difference vegetative index (NDVI), the chlorophyll SPAD unit pigments, and the Leaf Area Index (LAI) at the V6, V12, R1, and R6 stages for the control plot and the fertilizer-sprayed plot for both tested hybrids under irrigated conditions. In 2023, we recorded the values of the same parameters at the V12, R1, R4, and R6 stages for the control plot and the fertilizer-sprayed plot under irrigated and non-irrigated conditions. The Normalized difference vegetative index was utilized to asses the photosynthetic activity with the GreenSeeker Handheld meter serving as the measurement instrument. Relative chlorophyll content was assesed using a SPAD-502 chlorophyll meter (Konica Minolta, Japan). The recorded data was obtained from the uppermost mature leaf prior ear initiation, and subsequently from the leaf opposite to the ear, with 10 replicates being conducted for each measurement.

Regarding the LAI measurments, in the cropping season of 2022, we recorded leaf length and maximum leaf width to calculate the leaf area (cm²) and then the actual leaf area per plant, as outlined below:

Actual leaf area per plant = sum of the areas of individual leaves on each plant

Where: Leaf area (cm²) = leaf length (cm)*maximum leaf width (cm)*0.75

However, in 2023, we recorded the LAI measurements using sun scan.

As for the statistical analysis regarding the comparative analysis performed between the two years, we converted the values of Leaf area (cm²) obtained in 2022 to match the values of LAI recorded in 2023.

Plant height of the selected samples for the determination of dry matter and nutrient content was also measured using a meter ruler.

3.5.3 Yield parameters

The moisture, protein, starch and oil content of the grains were analyzed via the use of Perten DA7250 NIR infrared grain analyzer. Yield components were also determined after processing the samples into Haldrup precision equipment. Thus, the cob length was measured using a ruler, while the cob diameter and the stem diameter were measured using a digital Vanier Calliper, and the cob weight using an electronic balance. In addition, VSC-201 Vibrating Seed Counter was used to determine the thousand-grain weight, grain weight, and number of grains per cob. Grain yield (t ha^{-1}) was calculated at a moisture content of 14%.

3.6 Statistical analysis

Data were subjected to analysis of variance (ANOVA) using General Linear Models (GLM) to identify the significant differences between factor effects and interactions and the studied parameters. The means were then subjected to a Tukey’s test, which indicated significant mean differences at a p-value less than 0.05. The relationship between essential nutrients and yield, as well as between the grain yield quality traits and yield, was established using Pearson’s correlation. Statistical analysis was conducted using Minitab v20.4 software, while graphs were generated with both Minitab and MS Excel 365.

4. Results and Discussion

4.1 Results of the first cropping season, 2022, under irrigated conditions

4.1.1 Dry matter, nutrient accumulation, plant height and yield of maize in the growing season 2022

Maize dry matter and nutrient accumulation, plant height, and yield are addressed in this section for irrigated conditions during the 2022 season. The analysis was conducted in two phases: Phase A addressed whole-plant functionality across all phenological stages (V6-R6), while Phase B focused on organ-level nutrient partitioning from V12 to R6. This organizational structure permitted full exploration of temporal and spatial dynamics across hybrids, stages, and plant organs.

- Dry matter and nutrient accumulation in 2022 under irrigated conditions

4.1.1.1 Phase A

The accumulation of dry matter throughout the crop's growth cycle was strongly affected by the phenological stage ($p<0.001$), with no significant impact from the hybrids or interactions (Figure 9). Tukey comparisons revealed a marked increase in dry matter from V6 to V12, where it continued to increase until R2, after which the accumulation of dry matter slowed to R4. As the maturity stage approached, the growth trajectory of the plant increased once again. The increase in dry matter accumulation in the inflorescence can likely be explained by the redistribution and transfer of nutrients and photosynthetic products stored in senescent plant tissues to the inflorescence during the reproductive phase (Ferreira et al., 2023). The dynamic of dry matter content is connected with the loss of moisture content. Once the physiological maturity stage is reached, the active process prevails. This can be observed when the black layer in the kernels appears, which is a sign of establishing the maximum dry matter content at the maturity stage. The results showed that reaching the maturity stage, Fornad hybrid accumulated 1377 HU and produced a total of 23092.83 kg ha^{-1} of dry matter content, whereas 24476.05 kg ha^{-1} was produced by Mv 352 hybrid while accumulating 1352 HU in the maturity stage. These results exceed 16190 kg ha^{-1}, i.e the result obtained by Ferreira et al. (2023), and largely exceed the results found by Ravibabu et al. (2020).

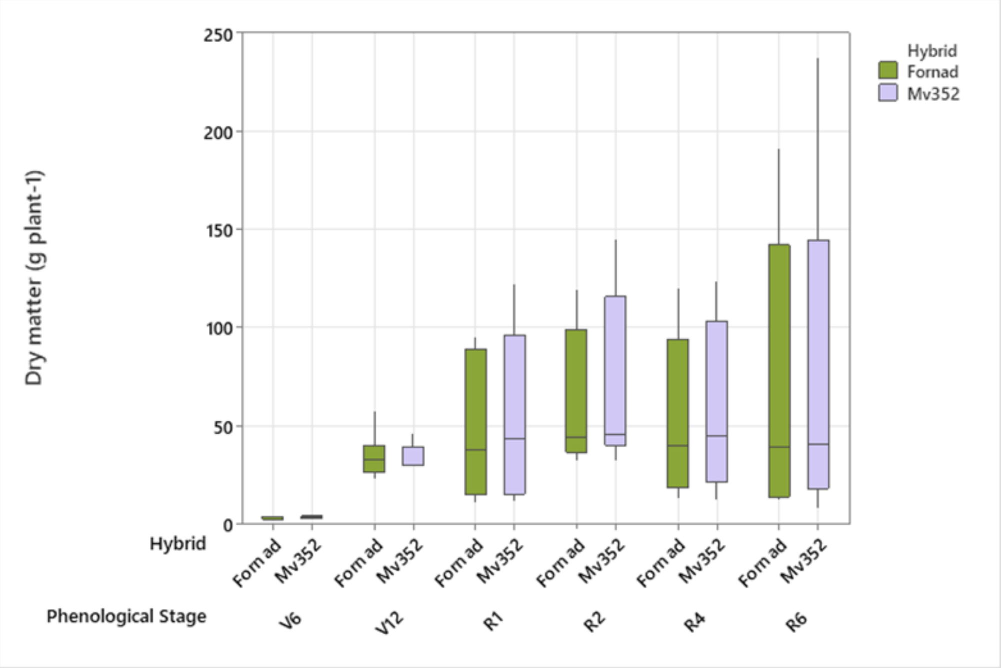

Figure 9. Dry matter uptake of maize as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

During the different stages of plant growth, maize primarily accumulated nitrogen, phosphorus and potassium, which are strongly affected by phenological stage ($p<0.001$). N and P accumulation showed a downward trend from early vegetative phases to maturity. While the trend of K uptake peaked in early stages (V6 and V12) and then decreased markedly towards R6. This trend indicates a physiological remobilization of nitrogen from the leaves and stalks to the reproductive organs and mainly to kernels (Figures 10, 11 and 12). The hybrid effect ($p<0.01$) was only present in the uptake of phosphorus, along with a significant interaction ($p<0.05$). Yet, Mv 352 accumulated the greatest nitrogen content at the end of the growing season, with 227.5 kg ha^{-1} surpassing the result of 185.7 kg ha^{-1} found by Ferreira et al. (2023), which in turn is close to our result obtained by Fornad hybrid (183.9 kg ha^{-1}). Fornad hybrid, however, had higher P accumulation than Mv 352, accumulating, respectively, 64.2 kg ha^{-1} and 43.9 kg ha^{-1} at the maturity stage. These results exceed the result obtained by Ferreira et al. (2023), which is 42.3 kg ha^{-1}. While analysing our results, it was surprising to observe the greater amount of potassium accumulated throughout the plant's developmental stages. At R6, K accumulation exceeded that of N and P accumulated by both hybrids. Thus, Mv 352 and Fornad accumulated 270.99 kg ha^{-1} and 250.96 kg ha^{-1}, respectively. By that, Mv 352 accumulates the greater K uptake. Our results, once again, largely exceed the result obtained in the study of Ferreira et al. (2023) (134.9 kg ha^{-1}).

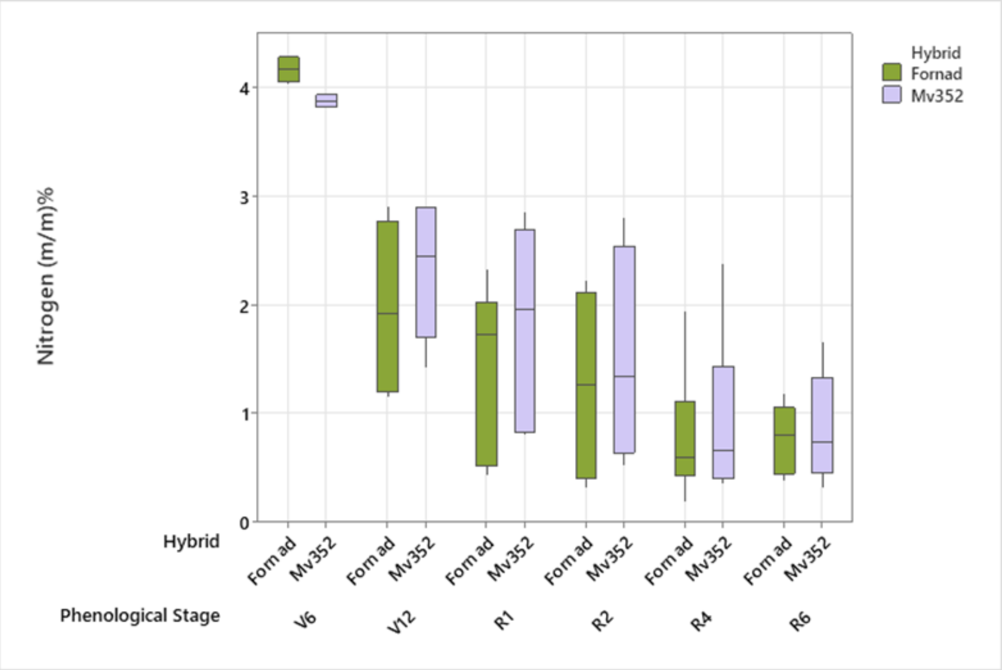

Figure 10. Nitrogen uptake of maize as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

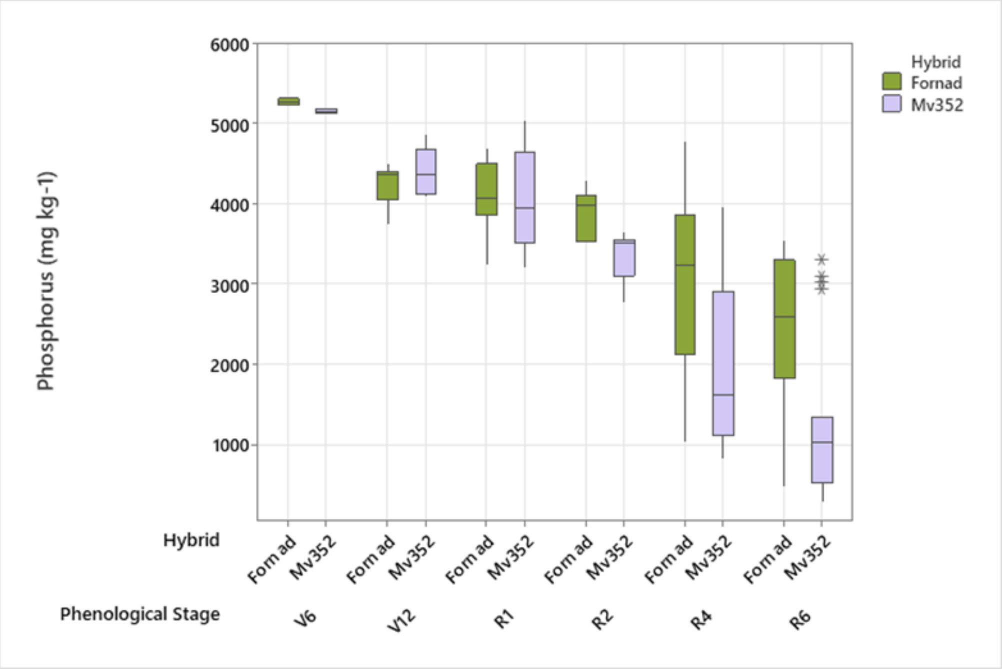

Figure 11. Phosphorus uptake of maize as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Interaction: p<0.05. (Debrecen, 2022).

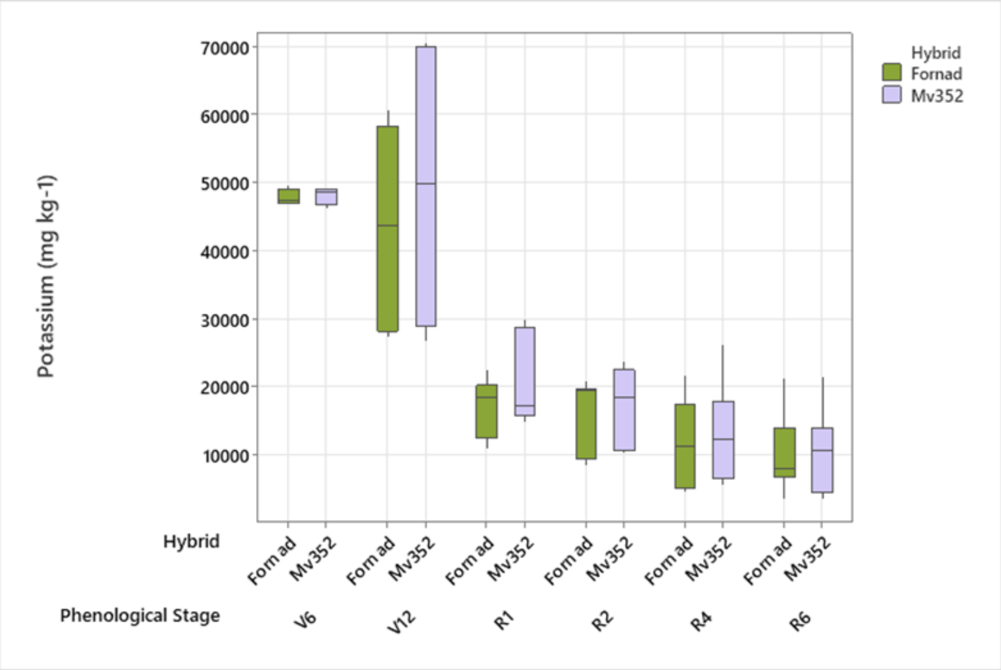

Figure 12. Potassium uptake of maize as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

Moreover, calcium ($p<0.01$) and magnesium ($p<0.001$) accumulations varied significantly across phenological stages. At V6 and V12, calcium uptake by both plants was high (Figure 13). From V12 through to R1, the accumulation of calcium decreased and increased once more upon reaching R2. Following this, it decreased up to R4 and went up once more to R6. This can be attributed to the low mobility of calcium and its structural role in cell membranes and walls. On the other hand, Mg accumulation trend showed a decreasing concentrations from early stages onwards till R6 (Figure 14). This pattern reflects the magnesium’s role in chlorophyll production and its remobilization during reproductive development. Their lack of hybrid significant differences may be attributed to localized distribution and low translocation capability. However, there was a slight difference between the hybrids, as Fornad accumulated a greater magnesium content than Mv 352 at R6. Fornad accumulated 18.74 kg ha^{-1} while Mv 352 accumulated 17.84 kg ha^{-1}. However, our results seem to indicate lower magnesium amounts compared to the 31.30 kg ha^{-1} obtained by Ferreira et al. (2023). On the other hand, Mv 352 accumulated 42.9 kg ha^{-1} of calcium, while Fornad accumulated 34.9 kg ha^{-1} of calcium. The results obtained exceed that of Ferreira et al. (2023), which is 15 kg ha^{-1}.

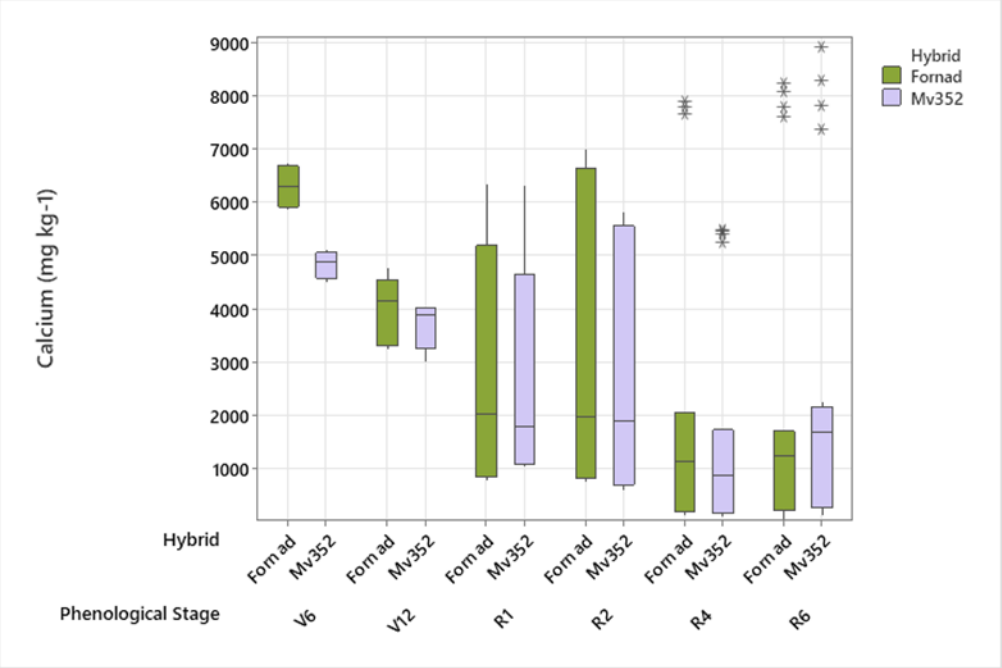

Figure 13. Calcium uptake of maize as a function of phenological stages. Phenological Stage effect: p<0.01 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

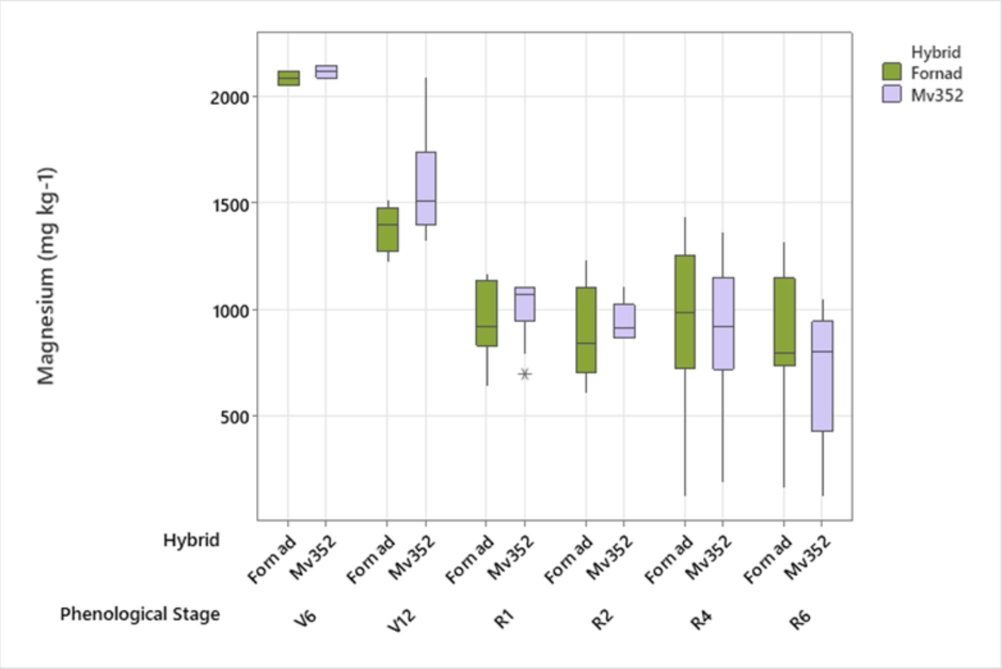

Figure 14. Magnesium uptake of maize as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

Sulfur accumulation also varied significantly by phenological stage (p<0.001). It was the greatest at V6 and V12, then declined through R6. This is reflective of sulfur's significant contribution to early protein synthesis and subsequent redistribution into developing grains. Tukey results maintained this pattern with the early stages grouping separately (Figure 15). Although hybrid and interaction effects were not significant, we can see that by the end of the growing season, Mv 352 had accumulated a higher sulfur content than Fornad (18.24 kg ha^{-1} vs. 17.13 kg ha^{-1}). This is much greater than the 5.2 kg ha^{-1} obtained by Ferreira et al. (2023), whose greatest accumulation was found to be at R3 with 10.84 kg ha^{-1}, which is far less than our results.

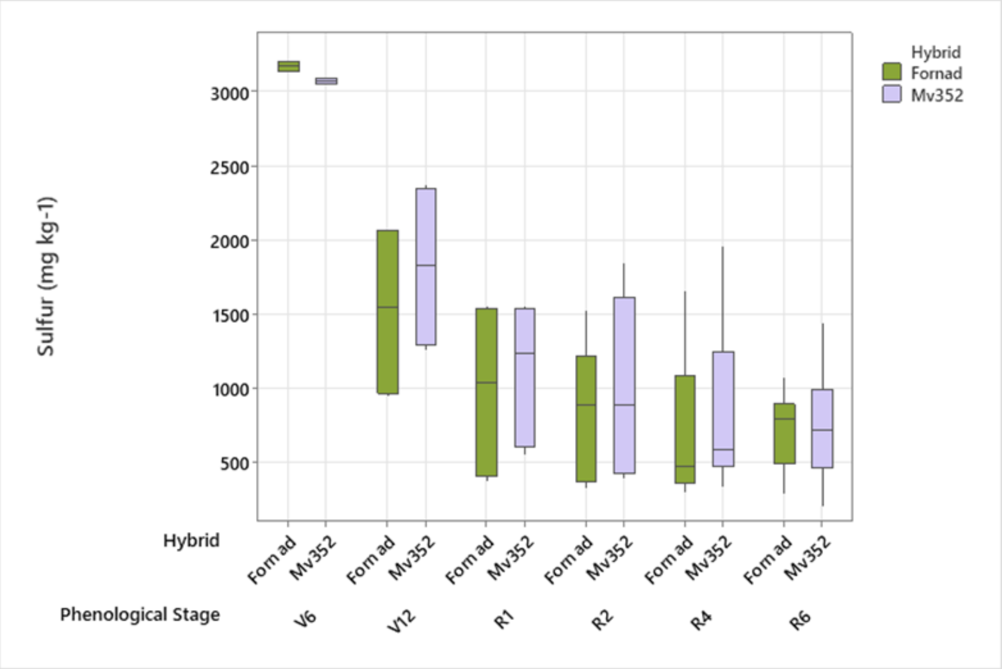

Figure 15. Sulfur uptake of maize as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

Micronutrients (Fe, Mn, Zn, Cu and B) accumulated in small but increasing amounts in maize during the season (Appendix 1). ANOVA showed no significant differences in Fe or Mn levels between stages or hybrids. By maturity, Mv 352 had accumulated 2.69 kg ha^{-1} of Fe, compared to 2.49 kg ha^{-1} for Fornad, both of which were higher than the 0.459 kg ha^{-1} reported by Ferreira et al. (2023). Mv 352 reached 0.65 kg ha^{-1} for Mn and Fornad reached 0.58 kg ha^{-1}, which they exceed the value of 0.22 kg ha^{-1} reported by Ferreira et al. (2023) and aligns with the value of 0.578 kg ha^{-1} reported by Oliveira et al. (2019). Boron ($p<0.05$), copper and zinc ($p<0.001$) uptake were significantly influenced by growth stages. Boron followed an oscillatory pattern, peaking at V6 and R1. At maturity, Mv 352 accumulated 0.14 kg ha^{-1} of B and Fornad accumulated 0.13 kg ha^{-1}, in which fall within the same range as those values reported by Borges et al. (2009) (0.11–0.13 kg ha^{-1}), but higher than the value reported by Ferreira et al. (2023) (0.072 kg ha^{-1}). However, copper levels decreased from V6 to R1 and then increased to a maximum at R6. By maturity, Fornad had accumulated 0.244 kg ha^{-1} of copper, which was slightly higher than the 0.238 kg ha^{-1} accumulated by Mv 352, which both values were well above the 0.099 kg ha^{-1} reported by Ferreira et al. (2023). Overall, Mv 352 accumulated more Cu accross the season. Similarly, zinc levels decreased from V6 to R4, then increased sharply at R6. By maturity, Fornad had accumulated 0.38 kg ha^{-1} of zinc, which was similar to the value reported by Ferreira et al. (2023), while Mv 352 accumulated 0.28 kg ha^{-1}. Nevertheless, these results were below the value reported by Oliveira et al. (2019) (0.606 kg ha^{-1}).

- Plant height of maize in 2022 under irrigated conditions

The plant height of maize hybrids significantly varied throughout growth stages ($p<0.001$), yet there was no statistical difference detected among the hybrids. In the early growth stages, the rate of plant height increases faster, but in the later stages it slows down (Shrivastava, 2021) (Figure 16). The increase in plant height was most pronounced at the R1 stage, after which it decreased and stabilized at maturity (stage R6). During the growing season, average plant height ranged from 32 cm to 325.5 cm. At the R1 stage, Mv 352 recorded the tallest plant, while Fornad recorded the shortest plant at the V6 stage. On average over the growing season, the Mv 352 hybrid had the highest plant height, at 238.67 cm, while the lowest belonged to the Fornad hybrid, at 237.20 cm (Figure 17).

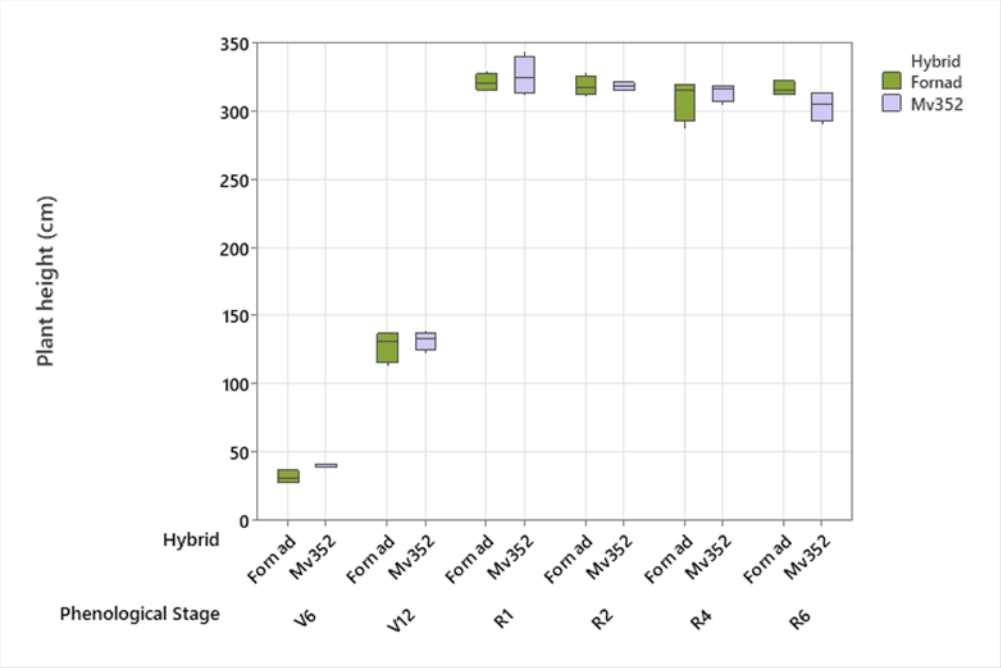

Figure 16. Plant height of maize as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

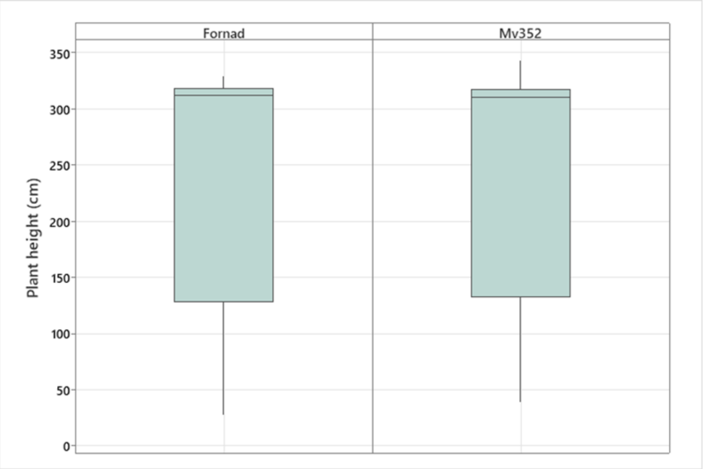

Figure 17. Plant height of maize. Phenological Stage effect: p<0.001 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

4.1.1.2 Phase B

Dry matter accumulation was significantly influenced by phenological stage (p<0.001) and plant part (p<0.001), but not by hybrid. This confirms the biological variation by development and organs. The results showed that, during the growing season, the most dry matter was accumulated by the stalks and leaves, particularly the stalks, until reaching R4, at which point accumulation shifted to the kernels. The V12 marks the first peak in dry matter accumulation, with the stalks in Mv 352 and Fornad accumulating 2285.79 kg ha^{-1} and 2462.49 kg ha^{-1}, respectively. Meanwhile, the leaves accumulated 1926.5 kg ha^{-1} and 1876.43 kg ha^{-1} in Mv 352 and Fornad, respectively. By the time they reached R1, the Mv 352 and Fornad maize hybrids had accumulated 41.05% and 38.13% of the total dry matter, respectively. From R1 to R2, the dry matter accumulation in the ears increased marking its development and grain formation. At R4, the dry matter content of the kernels was highest compared to the vegetative organs (7039.325 kg ha^{-1}) for the Fornad hybrid, followed by the stalk (7030.8 kg ha^{-1}). However, at this stage, the Mv 352 stalks accumulated the highest dry matter, with the kernels taking second place, accumulating 8109.6 kg ha^{-1} and 6649.345 kg ha^{-1}, respectively. At the maturity stage, Fornad's highest dry matter content was obtained by the kernels of 11249.3 kg ha^{-1} and followed by the stalks with 7580.59 kg ha^{-1} (Figure 18). While Mv 352 hybrid accumulated 1352 HU in the maturity stage producing a total of 24476.05 kg ha^{-1} of dry matter content. The highest dry matter content was obtained by the kernels with 11168.59 kg ha^{-1} and followed by the stalks with 8584.06 kg ha^{-1} (Figure 19).

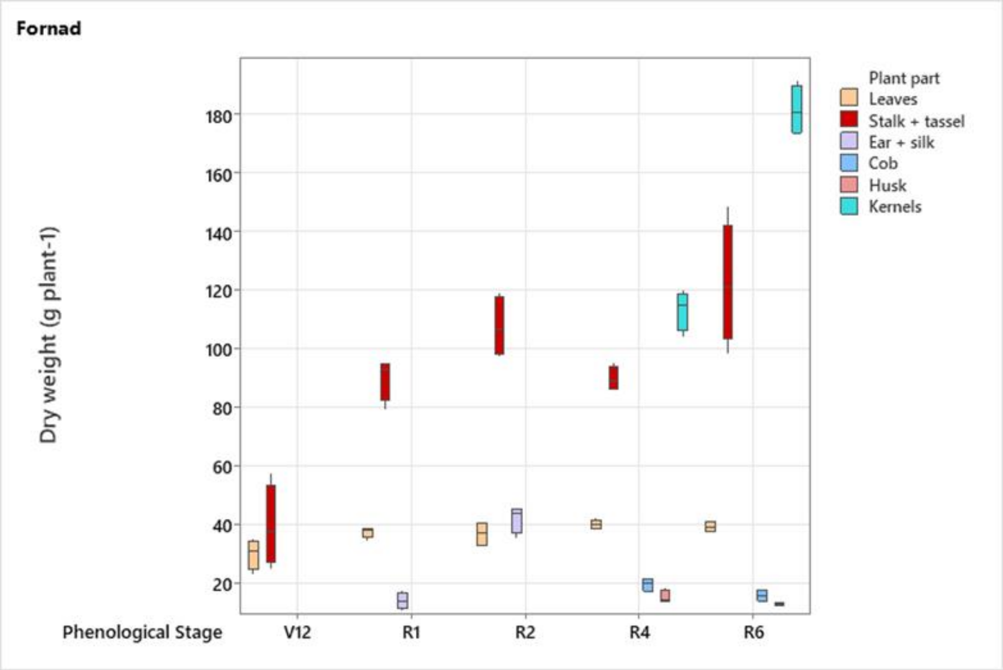

Figure 18. Dry matter accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2022).

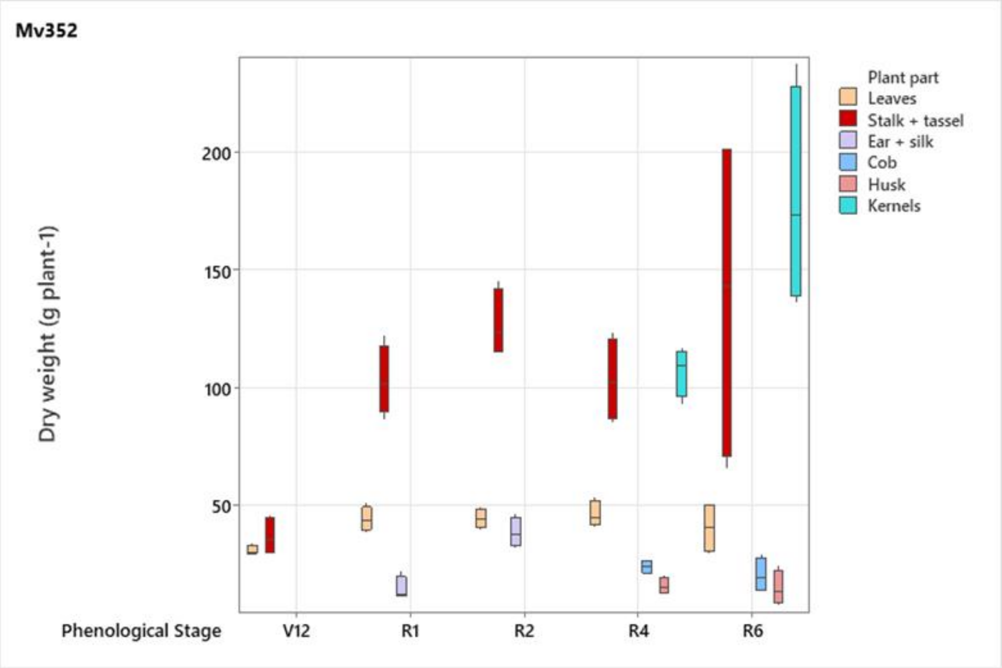

Figure 19. Dry matter accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2022).

Based on ANOVA, significant effects of phenological stage and plant parts on nitrogen, phosphorus and potassium contents. Hybrid effect was also strongly present for N uptake and moderately present for K uptake, as Mv 352 accumulated slightly more nitrogen and potassium than Fornad (Figure 20, Figure 21, Figure 24 and Figure

25). Hybrid*Plant Part interaction influenced nitrogen and phosphorus contents. While the interaction of Hybrid*Phenological Stage affected phosphorus accumulation. The variation in those nutrient concentrations across maize vegetative organs can be clearly observed in this study. Throughout the plant growth and development, N concentrations were high in plant vegetative organs, mostly in leaves, while P concentrations were high in plant vegetative organs, mostly in stalks, until reaching R4, where it shifted to the kernels. Prior to the silking stage, maize had the first peak of N, P and K uptake in the vegetative parts during the active vegetative growth stage, at V12, accumulating in Fornad and Mv 352, respectively, 44.4% and 41.8% of the total N content, 28.8% and 42.6% of the total P content and 215.69 kg ha^{-1} and 197.97 kg ha^{-1} of the total potassium content. In comparaison with N and P uptake, K nutrient demand by maize plants was significantly high, where as part of the vegetative organs, the stalk's demand for potassium was of major significance, as it required more potassium than nitrogen. Potassium uptake by the plants showed that 79.16% and 68.4% were absorbed by Mv 352 and Fornad, respectively, by the time of silking. While at the same stage, Mv 352 and Fornad had absorbed, respectively, 64.2% and 50.6% of total nitrogen content. Also, Mv 352 and Fornad had absorbed 87.8% and 55.7% of the total phosphorus content, respectively. The result obtained by Silva et al. (2018) (69%) is closer to ours. As maize transitions to the reproductive stages, nutrient allocation shifts to the ears and kernels development. Thus, during the reproductive and grain-filling phases, the uptake of N and P gradually decreased, reflecting its remobilization to the growing kernels, with nitrogen being more readily remobilized owing to its high phloem mobility (Kosgey et al., 2013). Only at R2, the accumulation of P content in the Fornad stalk increased a bit more to accumulate 27.45 kg ha^{-1} (Figure 22). At R4, Mv 352 and Fornad accumulated phosphorus, in kernels and stalks, respectively, 23.29 kg ha^{-1} and 10.16 kg ha^{-1}, and 26.26 kg ha^{-1} and 18.47 kg ha^{-1} (Figure 23). Nitrogen accumulation at the same stage by Mv 352 and Fornad accumulated in kernels and leaves, accounted respectively, 90.13 kg ha^{-1} and 64.41 kg ha^{-1}, and 75.81 kg ha^{-1} and 47.95 kg ha^{-1}. At R6, the maximum N accumulations were observed in the kernels at 138.19 kg ha^{-1} for Mv 352 and 112.10 kg ha^{-1} for Fornad. This was followed by accumulation in the stalk at 39.05 kg ha^{-1} for Mv 352 and 33.86 kg ha^{-1} for Fornad. The accumulated N content by maize kernels was found to be equal to 60.7% in Mv 352 and 61% in Fornad. Similar studies have indicated values of approximately 64% (Bender et al., 2013), 53% (Silva et al.,

2018) and, 74% (Ferreira et al., 2023). Moreover, at this stage, the maximum P accumulations were observed in the kernels at 34.52 kg ha^{-1} for Mv 352 and 29.09 kg ha^{-1} for Fornad. This was followed by accumulation in the stalk at 4.98 kg ha^{-1} for Mv 352 and 25.18 kg ha^{-1} for Fornad. Regarding potassium uptake, it was found that the maximum K uptake and accumulation was observed at R4, with Mv 352 achieving 100% of the total K, which is in accordance with Ferreira et al. (2023). In contrast, this was achieved at R6 for the Fornad hybrid. There was a hypothesis suggesting that the source of the concentration of nutrients in grains is either coming from post-silking absorption or remobilization of nutrients accumulated prior to silking (Yuhui et al., 2019). Unlike N and P, our study found that K uptake was higher in the vegetative parts of the plant than in the reproductive parts at the end of the growing season. The stalk was the organ that absorbed the greatest amount of potassium throughout the growing season. It means that the extent of K remobilization was the highest in the stalk, indicating that K was mainly remobilized from the stalk and less from the leaves. Moreover, we could observe that the extent of potassium translocation from the stalk and leaves to the kernels (13.12% for Mv 352 and 17.3% for Fornad of the total K at the maturity phase) was notably lower than that of phosphorus and nitrogen. For this reason, the grain-filling period does not appear to be critical in terms of potassium supply.

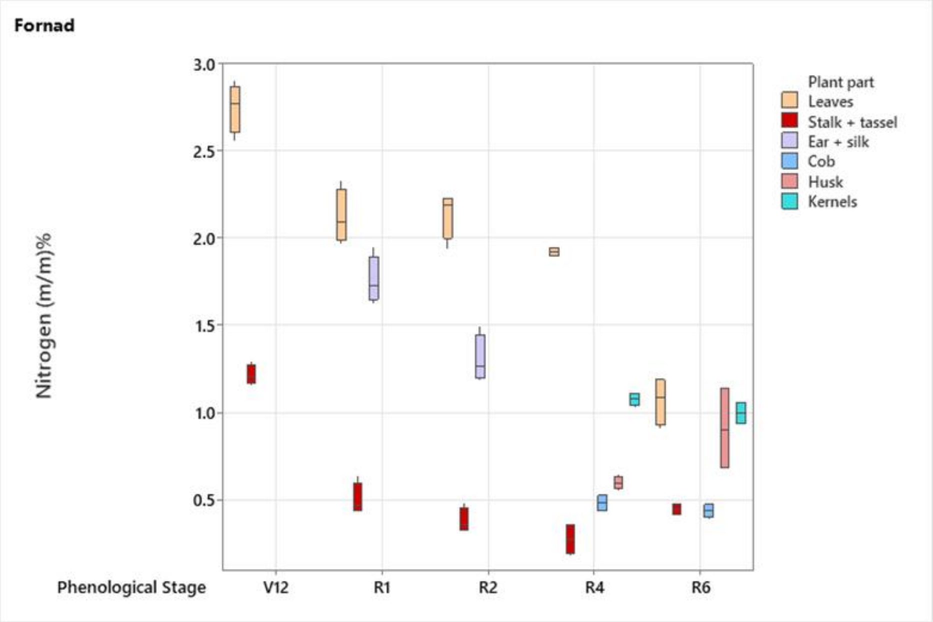

Figure 20. Nitrogen accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Plant Part: p<0.05. (Debrecen, 2022).

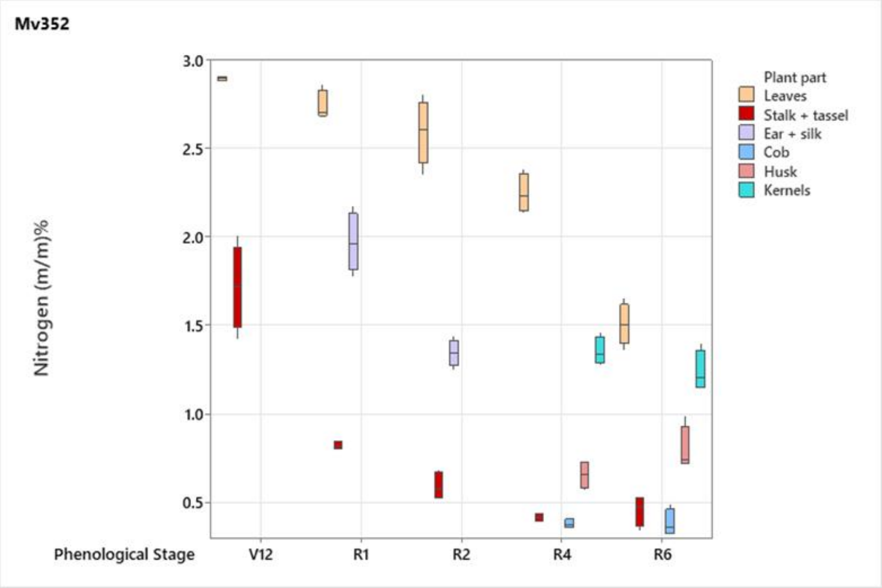

Figure 21. Nitrogen accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Plant Part: p<0.05. (Debrecen, 2022).

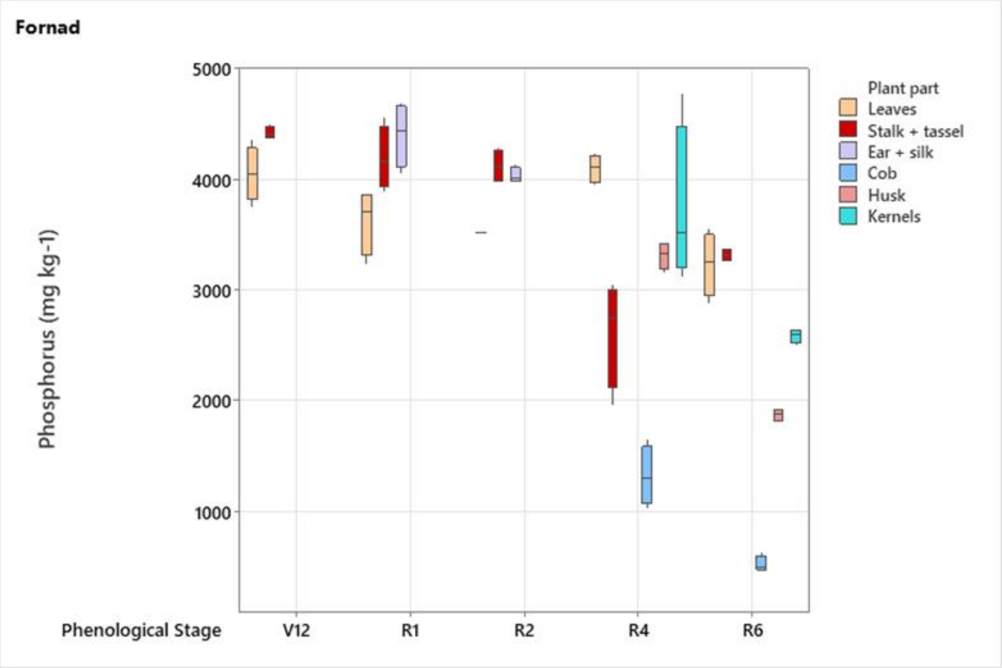

Figure 22. Phosphorus accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001. (Debrecen, 2022).

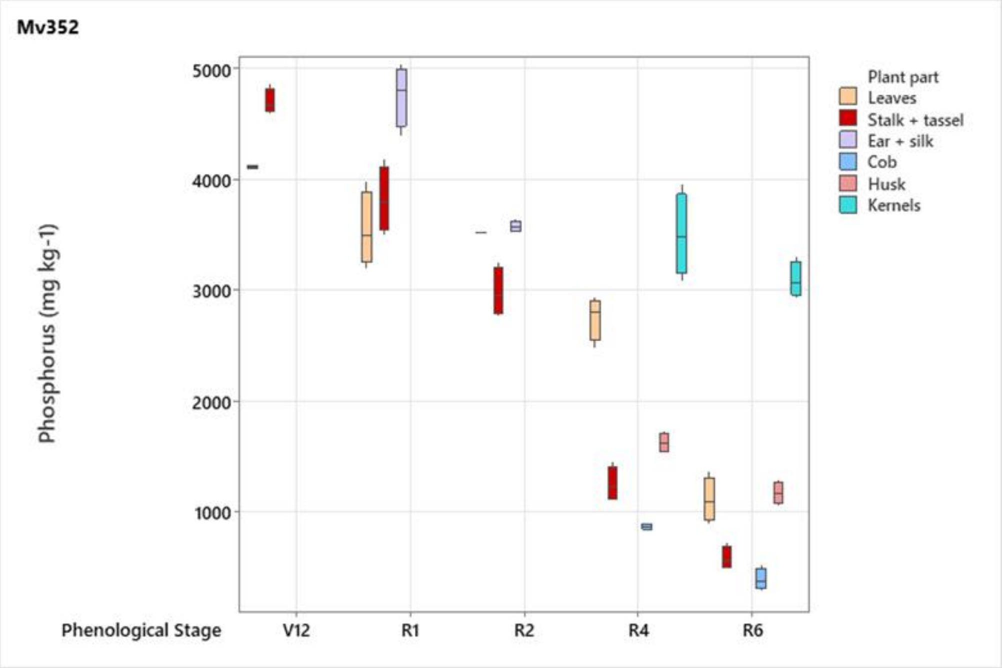

Figure 23. Phosphorus accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001. (Debrecen, 2022).

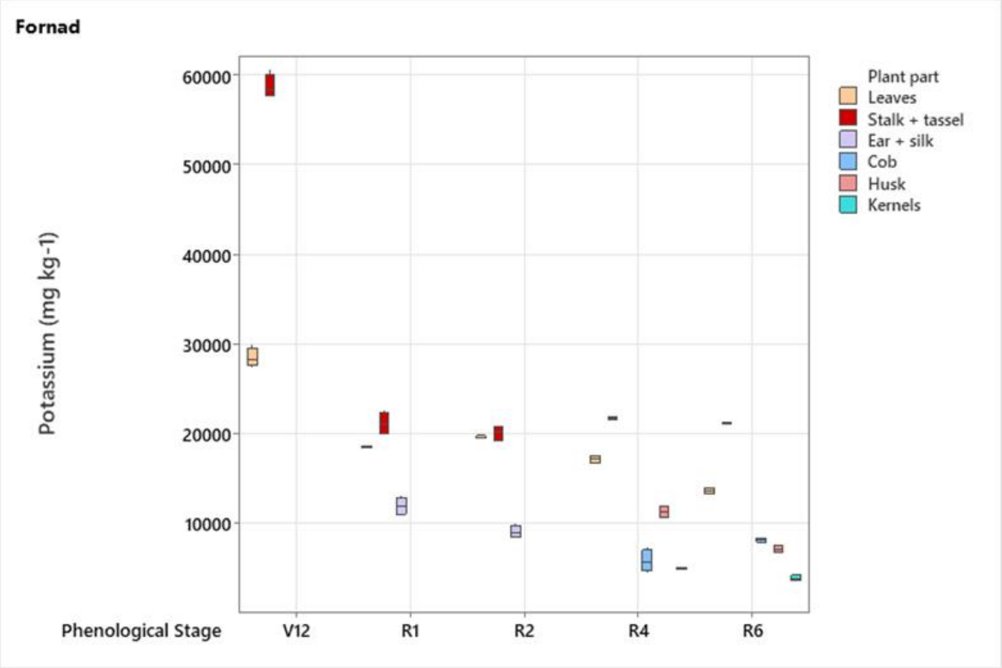

Figure 24. Potassium accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022).

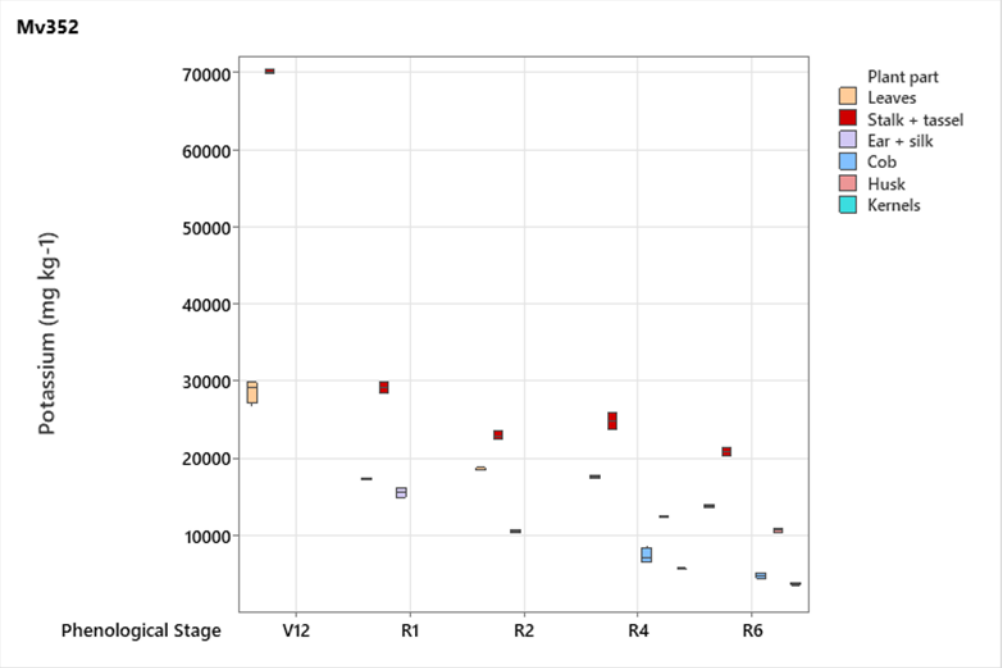

Figure 25. Potassium accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2022).

Calcium and magnesium were prominently affected by plant parts and phenological stage ($p<0.001$). Hybrid*Phenological Stage and Hybrid*Plant Parts interactions affected also magnesium accumulation. According to the Tukey test, the stalks and leaves had the highest calcium content, while the cobs and kernels had the lowest (Figure 26, Figure 27). These results are consistent with the limited mobility of calcium in the phloem. As the plants grew, maize Ca uptake peaked at V12, reaching 15.35 kg ha^{-1} in Mv 352 and 17.04 kg ha^{-1} in Fornad. It then reached a maximum value of 42.92 kg ha^{-1} at R6 for Mv 352, and 36.18 kg ha^{-1} at R4 for Fornad. Similarly, V12 was the first stage to show a small peak in magnesium uptake, getting 37.9% and 32.3%of the total magnesium content in Mv 352 and Fornad, respectively (Figure 28, Figure 29). By the time of silking, Mv 352 and Fornad had absorbed 57.4% and 41.7% of the total magnesium content, respectively. Unlike calcium, magnesium was mostly absorbed by the stalk. However, reaching R6, nutrient allocation shifts to the kernels. Mg accumulation in Mv 352 reached its maximum value of 19.85 kg ha^{-1} (100%) at R4 and then decreased as it approached the maturity stage with a final accumulation of 17.84 kg ha^{-1} in which 52.2% of total Mg content was present in the kernels. This value exceeds the total Mg absorption of kernels by 30%, as discovered by Silva et al. (2018). However, the maximum Mg accumulation value of 18.74 kg ha^{-1} (100%), in which 47.5% of total Mg content was present in the kernels. At this stage (R6), the leaves and stalks had the highest calcium content, followed by the kernels. The results for Mv 352 were 220.40 kg ha^{-1}, 16.86 kg ha^{-1}, 3.79 kg ha^{-1} for the leaves, stalk, and kernels, respectively, and for Fornad they were 119.45 kg ha^{-1}, 12.44 kg ha^{-1}, and 1.812 kg ha^{-1}. The accumulation of Ca in kernels is only 8.8% (Mv352) and 5.2% (Fornad) of total Ca. This is due to the nutrient's low mobility, which limits its redistribution to kernels.

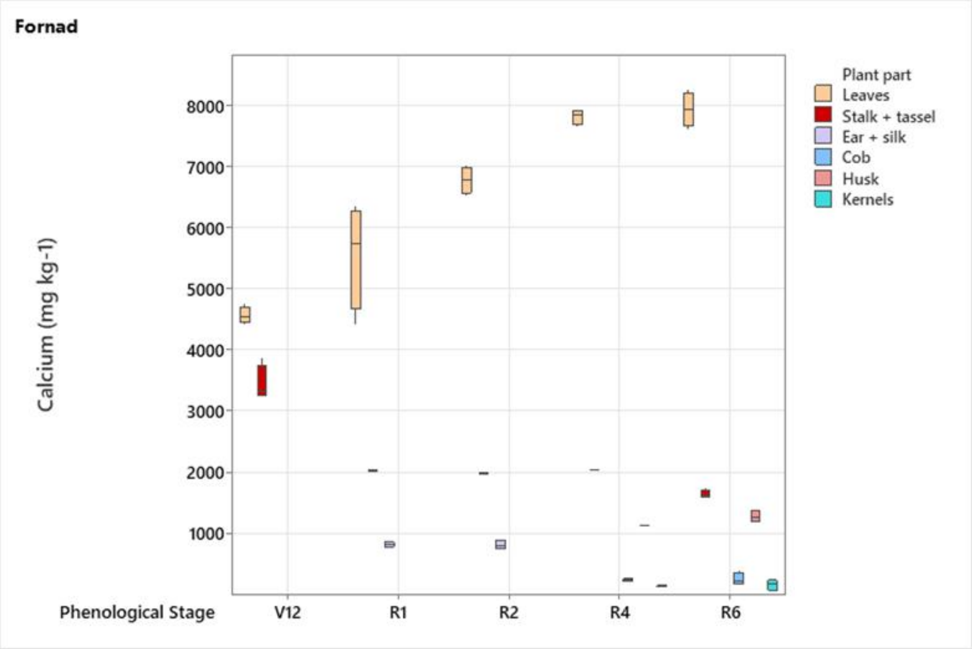

Figure 26. Calcium accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2022).

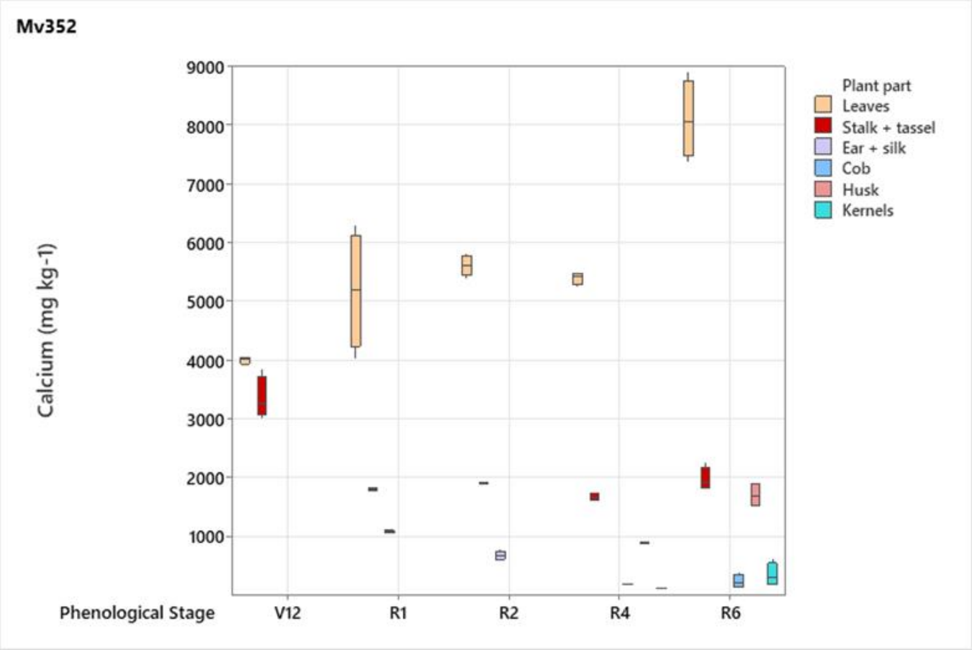

Figure 27. Calcium accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2022).

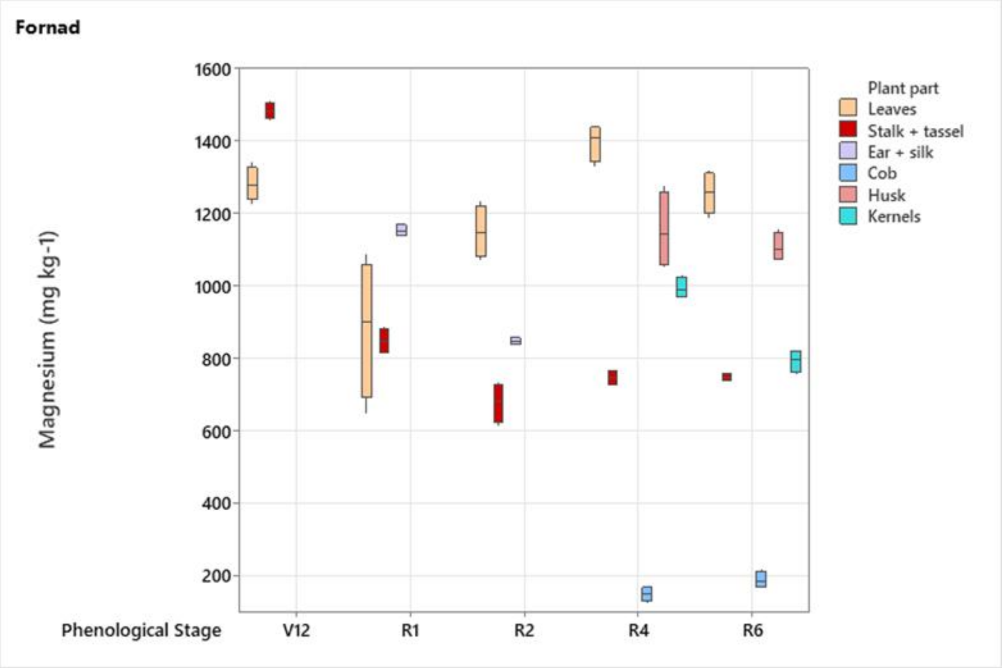

Figure 28. Magnesium accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.01, Hybrid*Plant Part: p<0.001. (Debrecen, 2022).

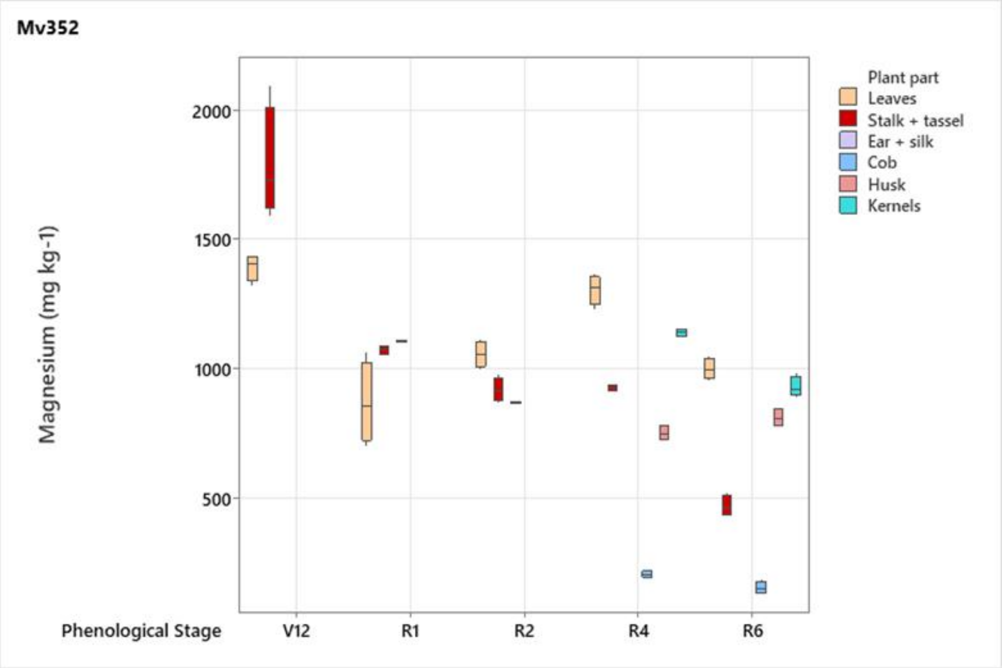

Figure 29. Magnesium accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.01, Hybrid*Plant Part: p<0.001. (Debrecen, 2022).

Sulfur content was significantly affected by hybrid, phenological stage and plant parts (p<0.001). During maize development, leaves accumulated higher S concentrations compared to stalks (Figure 30, Figure 31). The uptake and accumulation of sulfur in this organ is driven by its high metabolic activity and the need for sulfur for energy and protein synthesis. Throughout the growth stages, V12 marked the first peak, accumulating 41.1% and 36.7% of the total S content in Mv 352 and Fornad, respectively. By the time of silking, Mv 352 and Fornad had absorbed 50.1% and 39.3% of the total sulfur content, respectively. The kernels absorbed the most sulfur, followed by the leaves and then the stalks. This accounted for 7.807 kg ha^{-1}, 5.176 kg ha^{-1} and 3.842 kg ha^{-1} in Mv 352, and 7.523 kg ha^{-1}, 4.088 kg ha^{-1}, and 2.695 kg ha^{-1} in Fornad. During the reproductive growth stages, S accumulation exhibited some fluctuation in both the leaves and the stalk, reflecting sulfur's mobility and its use in amino acid synthesis during vegetative development. However, S concentrations in the ear components had an upward trend. This reflects on the continuous contribution of sulfur to the formation of chlorophyll, flowering, and seed formation. At R6, the total sulfur content was found to be 9.803 kg ha^{-1} (53.7%) in the kernels, 4.309 kg ha^{-1} (23.6%) in the stalk, 3.151 kg ha^{-1} (17.3%) in the leaves, 0.666 kg ha^{-1} (3.7%) in the husk, and 0.311 kg ha^{-1} (1.7%) in the cob in the case of Mv 352 hybrid. Similarly, at this stage, Fornad accumulated 9.886 kg ha^{-1} (57.7%) in the kernels, 3.815 kg ha^{-1} (22.3%) in the stalk, 2.456 kg ha^{-1} (14.3%) in the leaves, 0.639 kg ha^{-1} (3.7%) in the husk, and 0.328 kg ha^{-1} (1.9%) in the cob.

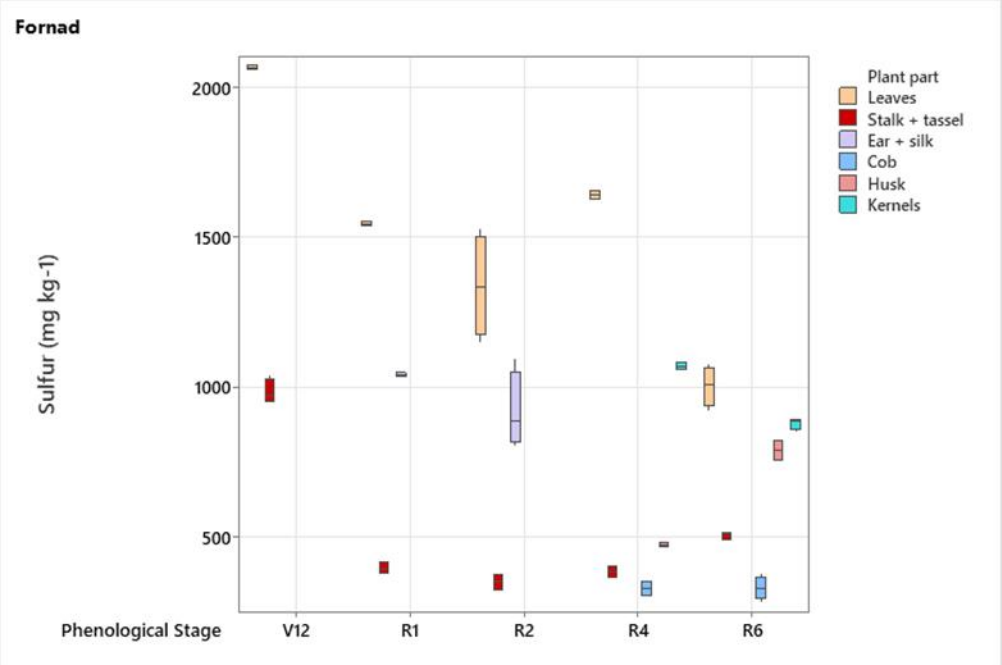

Figure 30. Sulfur accumulation within Fornad hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022).

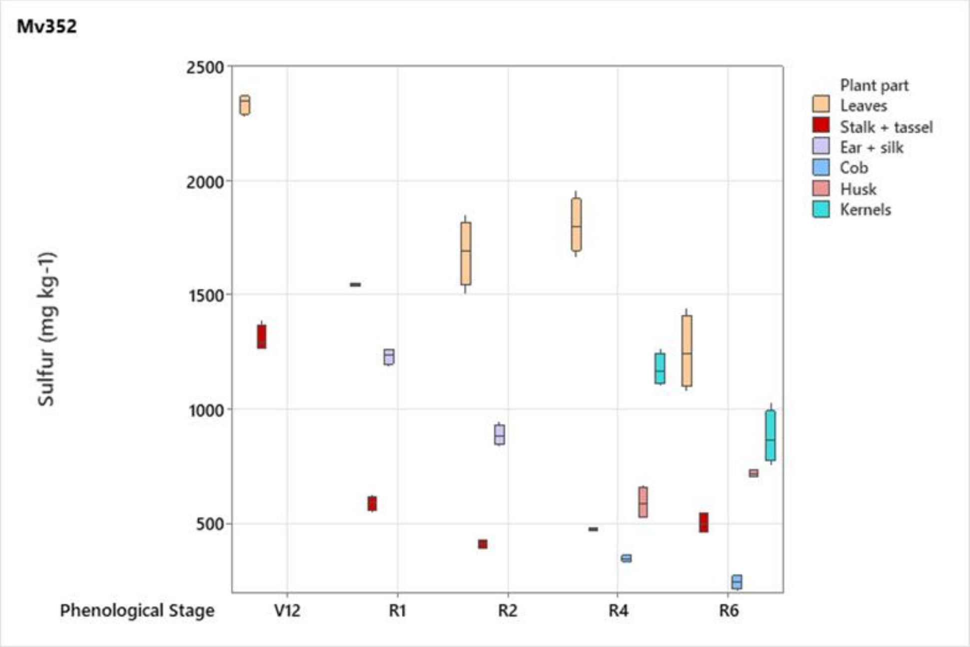

Figure 31. Sulfur accumulation within Mv 352 hybrid as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022).

The uptake of iron and manganese was strongly influenced by growth stage and plant part (p<0.001). V12 marked an early Fe peak of 27.3% (Mv 352) and 28.9% (Fornad), rising to 35.9% and 30.4% at silking, respectively (Appendix 2). Leaves accumulated the highest concentrations of Fe and Mn due to their metabolic demand, except for Mv 352 where the stalk took the predominance in Mn accumulation from R1to R4. At maturity, the total iron content was 2.69 kg ha^{-1} in Mv 352 hybrid and 2.5 kg ha^{-1} in Fornad. Corroborating with Ferreira et al. (2023) and to Oliveira et al. (2019) iron was the most extracted micronutrient by the plant. Manganese, on the other hand, peaked at R1 with 60.6% (Mv 352) and 44.5% (Fornad) of total Mn, followed by maximum uptake at R4 with 0.855 kg ha^{-1} (Mv 352), where the stalks stored the highest concentrations (0.397 kg ha^{-1}, i.e 46.46% of the total accumulation), and 0.898 kg ha^{-1} (Fornad), where the leaves stored the highest Mn concentrations (0.465 kg ha^{-1}, i.e 51.75%) (Appendix 2). Ferreira et al. (2023) reported a similar result, stating that the maximum Mn accumulation was 0.434 kg ha^{-1} at R3, but it was present in the kernels. At maturity, the total manganese content was found to be 0.65 kg ha^{-1} in the Mv 352 hybrid and Fornad 0.58 kg ha^{-1}. Boron content varied with phenological stage (p<0.001), plant parts (p<0.001), and, to some extent, with Hybrid*Phenological Stage interaction. Leaves stored the most boron due to its role in cell walls and meristematic growth (Bayar et al., 2024). Reproductive parts like cob and kernels contained significantly lower levels of B content, highlighting boron’s poor mobility and its sequestration in structural organs. By the silking, B uptake had reached 82.2% (Mv 352) and 79.6% (Fornad) (Appendix 2). At R4, B totalled 0.122 kg ha^{-1} (87.1%) and 0.124 kg ha^{-1} (95.4%), with most present in the leaves. Contrary to the findings of Perica et al. (2001), who found higher levels of boron in reproductive organs, this study revealed higher levels of boron in vegetative tissues. However, boron remained essential for reproduction (Devi et al., 2016; Kaur and Nelson, 2015). At R6, the highest boron accumulations were observed in the leaves, followed by the stalks and then the kernels. Accumulations were measured at 0.052 kg ha^{-1}, 0.043 kg ha^{-1}, and 0.034 kg ha^{-1} in Mv 352 and at 0.054 kg ha^{-1}, 0.034 kg ha^{-1}, and 0.031 kg ha^{-1} in Fornad. The total boron content was 0.13 kg ha^{-1} in Fornad and 0.14 kg ha^{-1} in Mv 352. Similarly, Cu was required by the plants in small amounts during active vegetative growth, and their concentrations usually increased as the plant progressed through the growing season. The uptake of copper by plants was significantly influenced by the phenological stage ($p<0.001$), the plant part ($p<0.001$) and the hybrid ($p<0.01$). Significant interactions were also observed between Hybrid*Phenological Stage and Hybrid*Plant Part. V12 marked an early peak of 0.026 kg ha^{-1} (Mv 352) and 0.021 kg ha^{-1} (Fornad). By the time of silking, Mv 352 and Fornad absorbed 10.5% and 5% of the total copper content, respectively (Appendix 2). The leaves had the highest concentrations of Cu. At R4, Cu reached 0.064 kg ha^{-1} (26.9%) and 0.044 kg ha^{-1}(18.1%) in Mv 352 and Fornad. At R6, maize kernels stored the most Cu with 0.079 kg ha^{-1} (Mv 352) and 0.105 kg ha^{-1} (Fornad), lower than values reported by Ferreira et al. (2023) (0.136 kg ha^{-1} at R5) and Borges et al. (2009) (0.30 kg ha^{-1}). The total copper content was 0.24 kg ha^{-1} in Fornad and 0.24 kg ha^{-1} in Mv 352. Zinc was significantly affected by hybrid, phenological stage, plant parts and their interactions ($p<0.001$), with Fornad accumulating more overall. V12 represented the first peak with 18.8% (Mv 352) and 13.9% (Fornad) of total Zn (Appendix 2). It was found that higher zinc concentrations were accumulated in the stalk. By silking, Zn uptake reached 36.1% and 20.4%, and at R4 Zn shifted to the kernels with 0.059 kg ha^{-1} (Mv 352) and 0.111 kg ha^{-1} (Fornad). At R6, the total zinc content was found to be 0.179 kg ha^{-1} (64.8%) in the kernels, 0.051 kg ha^{-1} (18.3%) in the stalk, 0.027 kg ha^{-1} (9.6%) in the leaves, 0.011 kg ha^{-1} (3.8%) in the husk, and 0.010 kg ha^{-1} (3.4%) in the cob in the case of Mv 352 hybrid. Similarly, at this stage, Fornad accumulated 0.196 kg ha^{-1} (51.5%) in the kernels, 0.083 kg ha^{-1} (21.8%) in the stalk, 0.039 kg ha^{-1} (10.4%) in the leaves, 0.022 kg ha^{-1} (5.7%) in the husk, and

0.041 kg ha^{-1} (10.7%) in the cob. The total zinc content was 0.38 kg ha^{-1} in Fornad and 0.28 kg ha^{-1} in Mv 352.

4.1.2 Correlation analysis of yield and the accumulated nutrient in maize under irrigated conditions, 2022

Based on the correlogram, the Fornad yield was strongly linked only with nitrogen uptake, indicating that its availability was critical for grain formation (Table 4). However, the correlations between the hybrid's yield and the other nutrients were either strongly or moderately negative, despite the crucial role of these nutrients in grain development. Unlike Fornad, the Mv 352 hybrid demonstrated strong positive correlations between its yield and each of the following nutrients: nitrogen, phosphorus, potassium, boron, calcium, copper, iron, magnesium, manganese, and sulfur. Therefore, a more robust relationship was achieved between these nutrients and the Mv 352 hybrid, implying a stronger reliance on these nutrients for yield-building processes such as kernel setting, efficient protein and enzyme metabolic activity, and energy transfer (P→ATP/ADP). However, there was a slight negative correlation between the hybrid yield and zinc.

Table 4. Correlations between maize yields and nutrient uptake under irrigated conditions. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p<0.05$. (Debrecen, 2022).

	Fornad	**Mv 352**
Nitrogen	**0.64**	**0.73**
Phosphorus	-0.55	**0.95**
Potassium	-0.70	**0.91**
Boron	-0.58	**0.80**
Calcium	-0.56	**0.81**
Copper	-0.66	**0.89**
Iron	-0.72	**0.93**
Magnesium	-0.48	**0.97**
Manganese	-0.73	**0.92**
Sulfur	-0.36	**0.91**
Zinc	-0.69	-0.22

4.1.3 Vegetative attributes response to foliar fertilizer treatment, 2022

- Soil Plant Analysis Development (SPAD)

SPAD was significantly affected by hybrid and phenological stage ($p<0.001$). Its values increased consistently from V12 to R1 and significantly peaked during R1 and declined slowly towards R6 (Figure 32). Mv 352 had significantly elevated SPAD levels com- pared to Fornad. Although the statistical variation was not significant the control and foliar fertilizer nutrition, the treatment had a positive effect on SPAD as it increased its values by 2%, 2.2% at R1 and R6, respectively, in Fornad hybrid. While, for the Mv 352 hybrid, the increase by the treatment was 3.4%, 2.4%, and 6.2%, at V12, R1, and R6, respectively. A similar study, conducted under comparable conditions, found that the 2021 drought was more intense than the 2022 drought. Balaout et al. (2022) reported that the same foliar nutrient application used in this study had a positive effect on the SPAD. Significant improvements of 12% and 4% were noted at V12 and R1 for the Mv 352 genotype, and 9% for the Mv Anissa genotype at R6. Furthermore, Zelenák et al. (2022) reported a 4.6% increase in SPAD values for the Ivola hybrid at R1. They also reported that the largest SPAD improvement observed in their study was achieved at R6 for Mv Marfi, at 16.2%, due to the foliar nutrition.

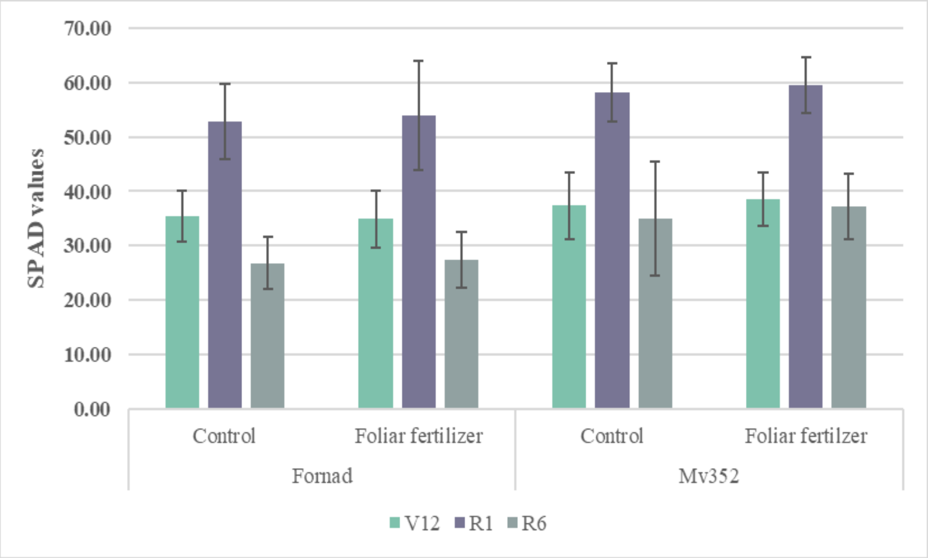

Figure 32. SPAD values of maize at different phenological stages under two treatment. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.001$ | Treatment: ns | Interactions: ns. (Debrecen, 2022).

- Normalised difference vegetation index (NDVI)

NDVI was significantly affected by hybrid ($p<0.01$), phenological stage, Hybrid*Phenological Stage, and Treatment*Phenological Stage interactions (p<0.001). Statistically, Fornad outperformed Mv 352, although the difference was minimal (Figure 33). The NDVI reached its highest values at V12, after which they declined upon reaching the maturity stage. Despite non-significant variations between control and foliar nutrition, there were negative responses of the hybrids towards the foliar treatments in the form of the decline in NDVI by 29.8% and 15% at R6 for Fornad and Mv 352, respectively, when compared to control. The only positive response towards foliar treatment in the form of NDVI values was found at R1 by a 10% increase in Mv 352. In a study conducted under similar conditions, where 2021 was characterized by a more intense drought than in 2022, Balaout et al. (2022) reported a positive effect of the same foliar nutrient application used in this study on the NDVI. They noted significant improvements of 8% and 25% at R1 and R6 for the Mv 352 genotype and 14% and 4.2% for the Mv Anissa genotype, respectively. Furthermore, Zelenák et al. (2022) reported an increase in NDVI of 6.3% at R1 and 4.9% at R6 due to foliar fertilization in the Ivola hybrid. Similarly, they observed smaller improvements in the NDVI of 4% and 2.7% at R1 and R6, respectively, in the Mv Marfi hybrid.

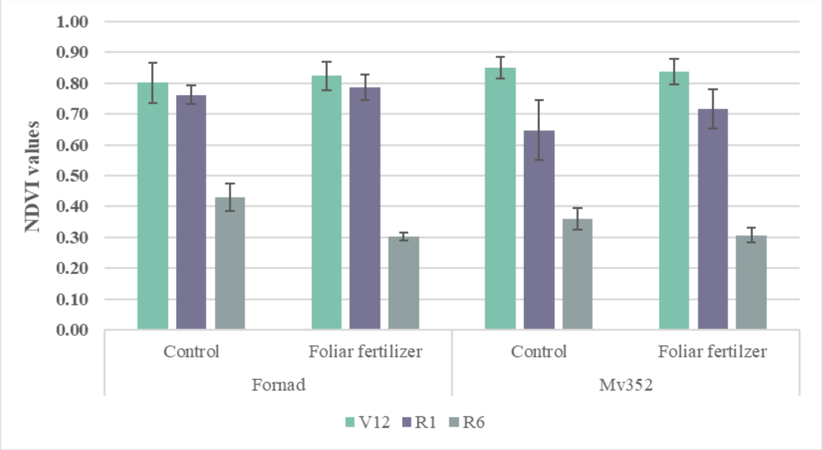

Figure 33. NDVI values of maize at different phenological stages under two treatments. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Treatment: ns | Interactions: Hybrid* Phenological Stage and Treatment*Phenological Stage: p<0.001. (Debrecen, 2022).

- Leaf area index (LAI)

The phenological phase contributed significantly to the LAI (p<0.001). Statistically, the hybrids were not different from each other; however, Mv 352 tended to have higher LAI values across R1 (+12.5%), R2(+8.2%), and R4(+2%) stages. LAI was significantly higher at R1, and it wasn’t significantly different from that recorded at R2 and R4 (Figure 34).

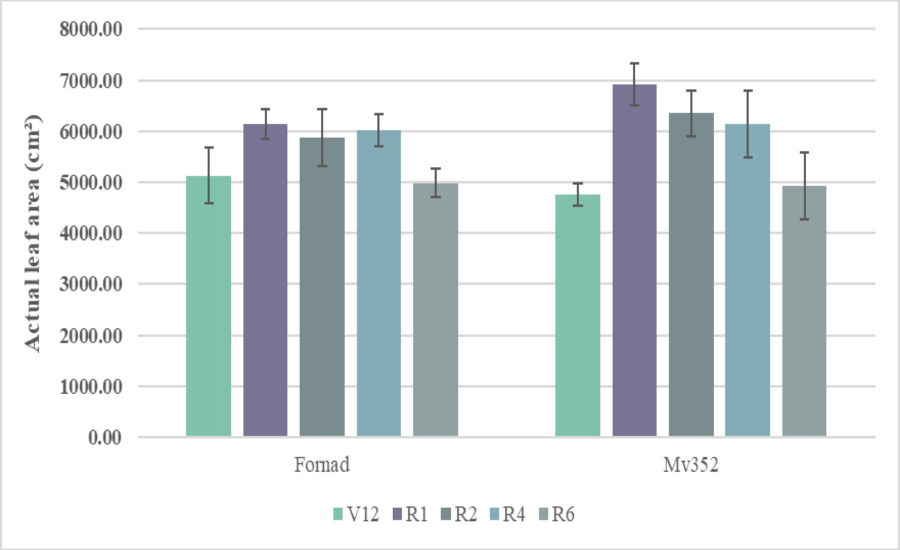

Figure 34. Actual leaf area of maize at different phenological stages. Phenological Stage effect: p<0.001 | Hybrid: ns | Interaction: ns. (Debrecen, 2022).

- Stem diameter

Only hybrid showed a significant effect on stem diameter (p<0.001) (Figure 35). Thus, Mv 352 possessed a thicker stem, indicating stronger structural support, likely resulting in improved kernel formation and ear support. However, the treatment effect was present even though it wasn't statistically significant, as it increased Fornad stem diameter by 6% compared to 0.4% of that related to Mv 352. El-Moursy et al. (2019) also discovered that spraying at varying levels of algae extract resulted in increased stalk diameter.

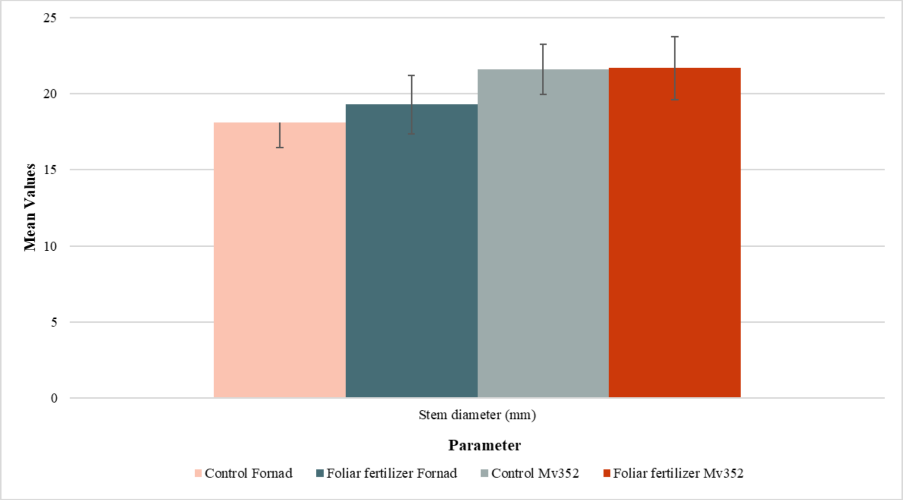

Figure 35. Maize stem diameter. Statistical significance was assessed using Tukey's test at (p<0.05). (Debrecen, 2022).

4.1.4 Grain quality traits response to foliar fertilizer treatment, 2022

Grain moisture content was not significantly affected by either hybrid or foliar fertilization (Figure 36). The values were nearly the same across treatments, which indicates that under irrigated conditions, grain desiccation proceeded similarly across hybrids and nutritional regimes. However, we can see that the foliar fertilizer increased the moisture content by 1.5% in Mv 352, while Fornad responded negatively to the treatment. In contrast to moisture content, oil content was significantly affected by Hybrid type ($p<0.05$). As a result, Mv 352 contained more oil content compared to Fornad. The interaction and foliar treatment were not significant, showing that the synthesis of oil is genetically determined most of the time. Yet, we can observe that hybrids showed a negative response to the treatment. Mv 352 had also significantly higher protein content than Fornad ($p<0.001$). Even where treatment effect was not significant, there was also a near positive treatment effect and since there was significant interaction, protein content was enhanced more in Fornad under foliar application by 10% whereas Mv 352 was reduced by 1%. This indicates potential hybrid-specific response to nutrition ($p<0.05$). Starch content, in the other hand, was strongly genotype-related ($p<0.001$), and also greater in Fornad, which contrasts with the aforementioned quality traits. Treatment and interaction were not significant, reflecting genetic control of starch accumulation, but the hybrids reacted negatively to the treatment.

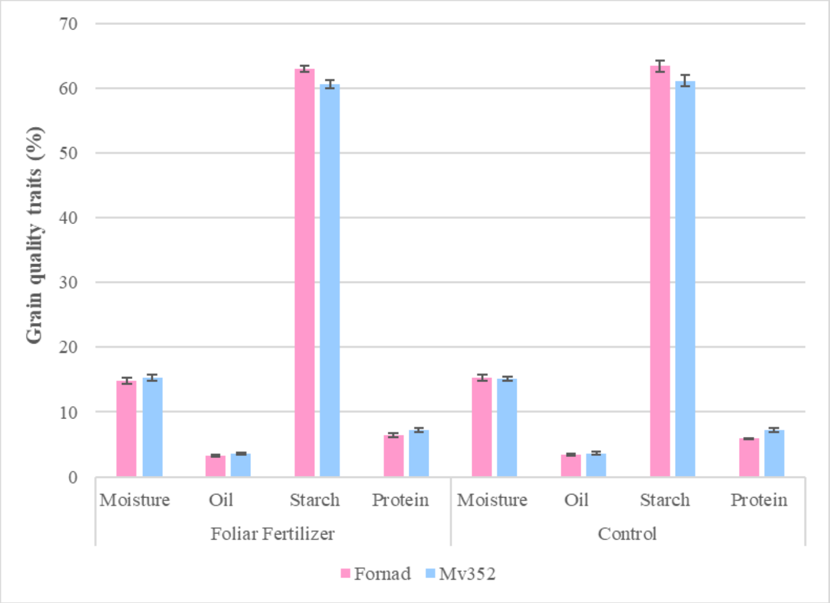

Figure 36. Grain quality traits of maize. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2022).

In line with our study, Tóth et al. (2022) found that the applied treatments did not significantly affect the quality parameters, including protein, starch, and oil contents. However, Jakab et al. (2021), in their study, found that foliar fertilization positively influenced the crop response to the applied treatment despite being considered a small effect. Compared to the control plot, the grain protein content was 7.8%, while it varied between 7.22% and 7.82% under the influence of foliar fertilization. The starch content of corn grain varied between 71.93% and 72.27% in the treated plot, while it was 71.93% in the control treatment. Similarly, in our study, the protein content fall into the same range. In the control plot, it was 5.89% for Fornad and 7.27 % for the Mv 352 hybrid. The positive influence of foliar fertilizer was observed only with the Fornad hybrid, as it was increased by almost 10 % (6.48 %) while that of Mv 352 was decreased by 1 % (7.19 %). In contrast, foliar fertilization slightly improved the grain moisture content of the Mv 352 hybrid by 1.5 % (15.32 %), which was 15.09 % in the control plot. While, in the case of the Fornad hybrid, there was no positive effect of foliar fertilizers, and it was slightly decreased by almost 3 % (14.84 %), which was 15.24 % in the control. Regarding the negative responses to foliar fertilizers (starch and oil contents), it could be related to other external factors, for instance, the changes in weather conditions, as well as to the difference in the nature of the hybrid itself, which was statistically proven. In line with our study, Lutã et al. (2022) reported in their study that the use of two different organic foliar fertilizers (CODAMIX and ECOAMINOALGA) had a positive impact on protein content. For instance, when using CODAMIX, the protein content of maize grains increased by 4.62%, while using ECOAMINOALGA, it increased by 13.87%, compared to the control. Additionally, they found that those biostimulants slightly increased the starch content of maize grains by 0.06% for CODAMIX and 0.35% for ECOAMINOALGA. This contradicts our findings on starch content.

4.1.5 Grain yield attributes response to foliar fertilizer treatment, 2022

- Thousand-grain weight, number of grains per cob, cob and grain weights

Hybrid significantly influenced thousand-grain weight and with Mv 352 having heavier grains. Thousand-grain weight was less sensitive to foliar nutrition but may contribute to yield differences (Figure 37). Despite its non-significance, the treatment increased the weight of Fornad 1000 grains by 10%. This hybrid also produced significantly more grains per cob than Mv 352 ($p<0.001$). There was no effect of treatment observed, suggesting a large genetic basis with limited physiological plasticity under foliar fertilization. Yet, the treatment increased the number of grains per cob in Fornad by 11.4%. In contrast, regarding cob weight, significant effects of the treatment and hybrid were observed. Cob weight was enhanced through foliar nutrition (p<0.05), with Mv 352 showing overall heavier cobs (p<0.001). However, the effect of the foliar fertilizer was more pronounced in Fornad, where it increased the weight of its corn cobs by 44.6%, compared to 4% for Mv 352. This illustrates an interaction between genetic potential and nutrient availability. Regarding grain weight, it was statistically influenced by foliar treatment and Treatment*Hybrid interaction (p<0.01). That explains how Fornad reacted more positively to foliar nutrition than Mv 352 during grain filling. For instance, due to the treatment, Fornad grain weight increased by 23% compared to Mv 352's 1.5% reduction. Badawi et al. (2012) found that spraying plants with biostimulants such as Melagrow or Aminototal 25 and 35 days after sowing had a significant effect on the weight of the ears and the 100-grain weight. Al-Ani et al. (2020) also reported higher ear grains weight due to the application of foliar biostimulants and nutrient-rich sprays (such as trader fertilization Fert-plus (20:20:20, NPK), Amino acid (AA), yeast essence (YE) and mix Fert-plus powder (20-20-20, NPK) + amino acids (AA) + yeast extract (YE)). Moreover, El-Moursy et al. (2019) found a significant effect on yield components (grain weight per ear, 100-grain weight, and number of grains per ear) in their study due to spraying with different levels of algae extract.

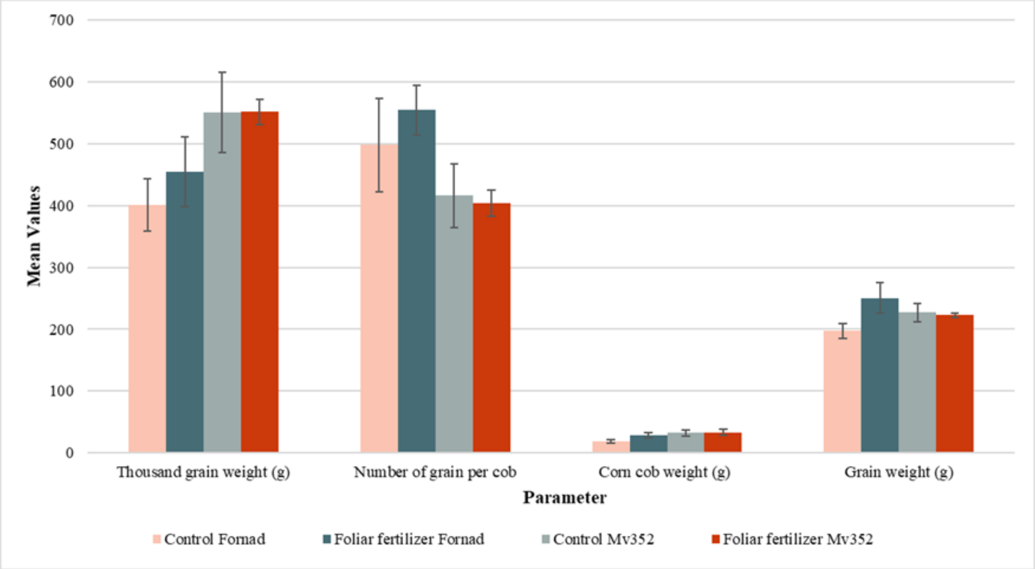

Figure 37. Maize grain attributes. Statistical significance was assessed using Tukey's test at (p<0.05). (Debrecen, 2022).

- Ear length, ear height, ear weight and ear diameter

Ear length was considerably greater in Fornad (p<0.001)and showed a significant Hybrid*Treatment interaction (p<0.05). This suggests that foliar fertilizer enhanced ear elongation more in Fornad than in Mv 352 (7.6% increase vs 1.6% decrease, respectively) (Figure 38). Besides of the hybrid and the hybrid*treatment interaction effects ($p<0.001$), ear height was influenced by hybrid ($p<0.001$). For instance, Mv 352 had taller ear but the foliar nutrition reduced height slightly (11% reduction), possibly suggesting altered plant genomic. Ear weight, on the other hand, was significantly affected by the treatment and Treatment*Hybrid interaction ($p<0.01$). This shows that genotype and foliar feeding interact to affect ear weight. Due to the effect of foliar fertilizer, Fornad ear weight was increased by 25%. The treatment also significantly increased ear diameter ($p<0.01$). This change reflects improved grain set or filling within ear structure under enhanced nutrition. Despite the non significance among the hybrids, we still can see that their response to the treatment was different (7% vs. 2.5% increase for Fornad and Mv 352, respectively). Al-Yasari and Al-Jbwry (2024) reported a significant improvement in average ear length. The highest mean ear length (18.90 cm) was observed when maize plants were sprayed with the organic nutrient potassium humate at a rate of 2 g L^{-1} while at a rate of 1 g L^{-1}, the mean ear length was 17.32 cm. Al-Ani et al. (2020) reported the application of foliar biostimulants and nutrient-rich sprays (such as trader fertilization Fert-plus (20:20:20, NPK), Amino acid (AA), yeast essence (YE) and mix Fert-plus powder (20-20-20, NPK) + amino acids (AA) + yeast extract (YE)) significantly increased growth characteristics, including ear length and ear diameter. Similarly, Badawi et al. (2012) reported a positive response to foliar spraying with biostimulants such as Melagrow or Aminototal, 25 and 35 days after sowing, resulting in the longest ears, largest ear diameter and heaviest ear weight.

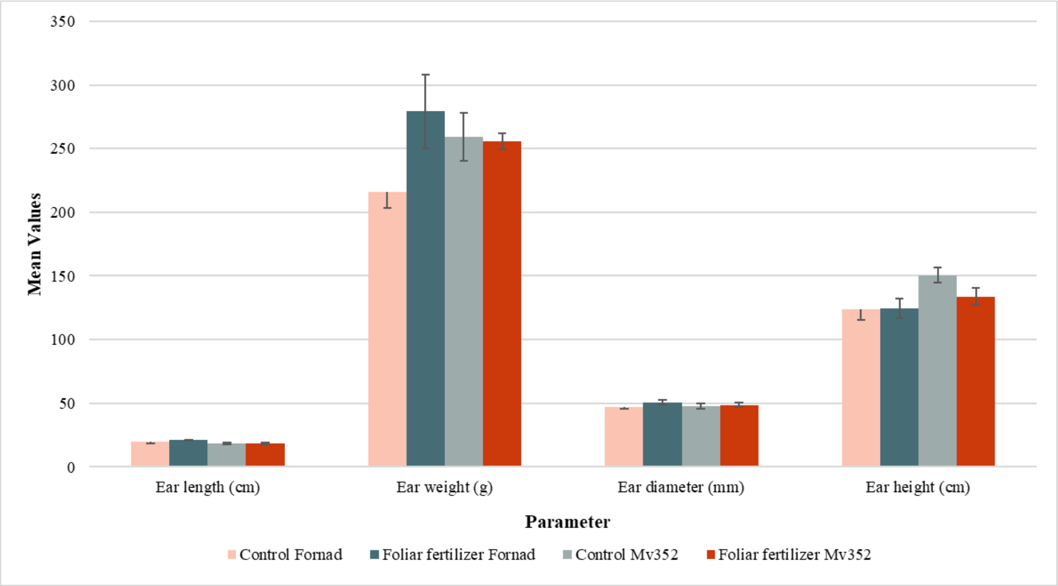

Figure 38. Maize ear characteristics. Statistical significance was assessed using Tukey’s test at ($p<0.05$). (Debrecen, 2022).

4.1.6 Grain yield in 2022

The treatment effect was statistically significant ($p<0.001$) (Figure 39). Based on our results, without applying foliar fertilizers, the yield of the Mv 352 was 13.273 t ha^{-1}, i.e. 312 kg lower than that of Fornad hybrid (Figure 40). The overall grain yield was significantly improved by foliar fertilization, with a bit more than 7% in grain yield. In addition to that, Fornad yielded slightly more than Mv 352, which was statistically significant ($p<0.05$). For instance, an increase of 7.6% (14.62 t ha^{-1}) and 7.2% (14.23 t ha^{-1}) in yield was obtained by Fornad and Mv 352, respectively, as a result of foliar nutrition application. Lack of interaction suggests consistent yield advantages from treatment for both hybrids. Jakab et al. (2021), reported that the foliar fertilizers used in their study increased corn yield compared to the control, but this increase was not significant in either case. For instance, when applied individually, the foliar fertilizers resulted in a surplus yield of between 0.19 and 1.07 t ha^{-1} compared to the untreated plot. The highest yield increase was achieved with the Algafix treatment (1.07 t ha^{-1}). When the products were applied in combination, the surplus yield compared to the untreated plot was 0.64 to 1.02 t ha^{-1}. The greatest increase in yield (1.02 t ha^{-1}) was observed in the Amalgerol + Fitohorm Turbo Zn treatments. Limon-Ortega and Baez-Perez (2024) also reported that foliar P fertilizer enhanced grain yield in their study. Similarly, Tejada et al. (2018), found that the use of biostimulant foliar fertilizers improved the yield by 13.4%. Al-Yasari and Al-Jbwry (2024) reported that the use of foliar fertilizers increased maize yield. For instance, using foliar fertilisers containing the organic nutrient potassium humate at a rate of 2 g L^{-1} resulted in the highest grain yield (8.52 t ha^{-1}) in maize plants. This was compared with a lower concentration of 1 g L^{-1} which provided the lowest average for this trait (7.53 t ha^{-1}), resulting in an increase of 13.14%.

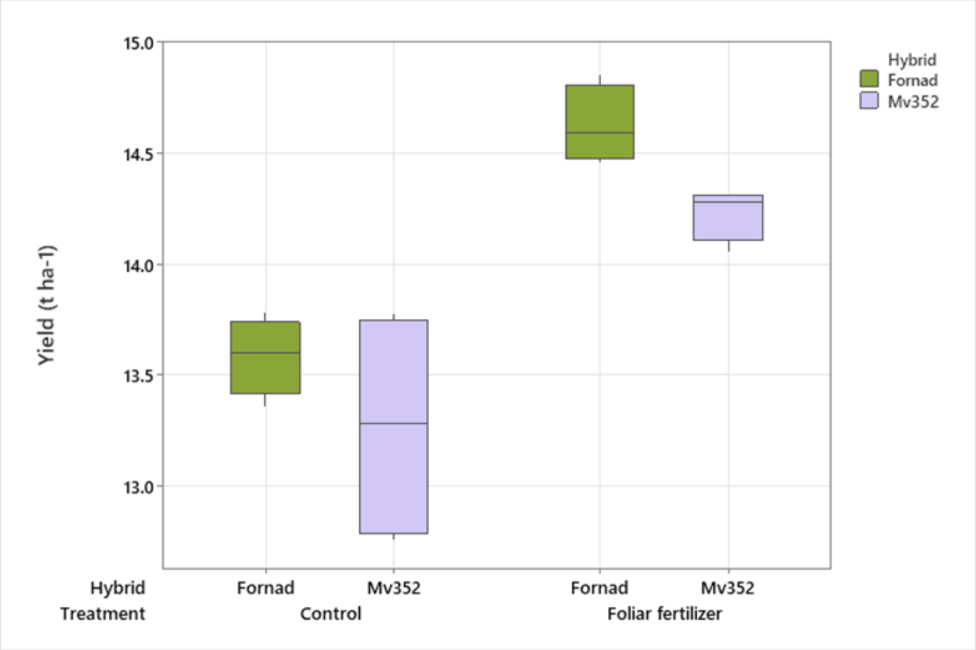

Figure 39. Grain yield of maize in response to foliar fertilization. Treatment effect: p<0.001 | Hybrid: p<0.05 | Interaction: ns. (Debrecen, 2022).

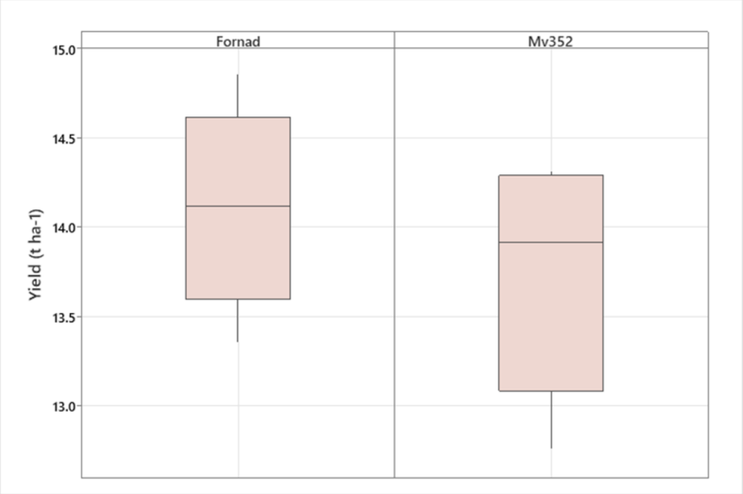

Figure 40. Maize grain yield. Treatment effect: p<0.001 | Hybrid: p<0.05 | Interaction: ns. (Debrecen, 2022).

4.1.7 Correlation analysis between grain quality traits and yield, 2022

The correlation analysis of protein content and yield in Fornad hybrid showed a highly positive correlation, while the correlation was not significant in Mv 352 (Table 5). There was also a strong negative relationship with oil content and a weak negative trend with starch and moisture contents. Mv 352 hybrid, however, showed slight positive correlations between yield and oil content, a greater correlation with moisture content, and a weak correlation with protein, suggesting that its accumulation was independent of yield.

Table 5. Correlations between maize yield and grain quality traits. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p<0.05$. (Debrecen, 2022).

	Moisture	**Oil**	**Protein**	**Starch**
Fornad	-0.14	-0.57	**0.66**	-0.08
Mv 352	0.44	0.37	0.03	-0.73

4.2 Results of the second cropping season, 2023, under two water regimes (irrigation and non-irrigation)

4.2.1 Dry matter and nutrient accumulation, plant height and yield of maize in the growing season 2023

This section gives a comprehensive description of maize dry matter, nutrient dynamics, plant height and yield, under irrigated and rainfed conditions during the 2023 growing season.

- Dry matter and nutrient accumulation in 2023 under irrigated and rainfed conditions

Dry matter accumulation was significantly influenced by phenological stage and plant part but not by treatment or hybrid (Figure 41). This indicates that water stress did not significantly impact total biomass production, reflecting physiological tolerance. However, considerable differences existed among stages and plant organs, indicating typical biomass partitioning (Figure 42, Figure 43). The maturity stage accumulated the maximum dry matter, while minimum accumulation was found to be at V12. The results showed that, during the growing season, the most dry matter was accumulated by either the leaves or the stalks until reaching R4, at which point accumulation shifted to the kernels. Yet at this stage, we noticed that the maximum dry matter accumulation was absorbed by the stalks, in Fornad under irrigated conditions and in Mv 352 under non-irrigated conditions. The V12 marks the first peak in dry matter accumulation, with the leaves in Mv 352 and Fornad accumulating 7.2 % and 8.5 %, respectively, under irrigated conditions, and 8.6% and 5.9%, respectively, under non-irrigated conditions. Meanwhile, the stalks accumulated 5.3 % and 5.5 %, respectively, under irrigated conditions, and 7.4% and 3.9%, respectively, under non-irrigated conditions. By the time they reached R1, the Mv352 and Fornad maize hybrids had accumulated 42.05% and 57.04% of the total dry matter, respectively, in irrigated conditions. Meanwhile, their accumulations under non-irrigated conditions were 45.13% and 34.10%, respectively. At R4, the dry matter content of the kernels was highest compared to the vegetative organs (6746.03

kg ha^{-1}) for the Mv352 hybrid, followed by the stalk (6666.08 kg ha^{-1}) under irrigated conditions. However, the maximum dry matter content in Fornad hybrid was absorbed by the stalks and followed by the kernels, accumulating respectively, 5356.65 kg ha^{-1} and 5283.53 kg ha^{-1} under irrigated conditions. Under non-irrigated conditions, the Mv 352 stalks accumulated the highest dry matter, with the kernels taking second place, accumulating 7150.65 kg ha^{-1} and 5746.49 kg ha^{-1}, respectively. While, Fornad accumulated the highest dry matter in the kernels with 6780.48 kg ha^{-1} followed by that absorbed by the stalks with 5711.55 kg ha^{-1}. The results showed that the Fornad hybrid accumulated 1319.8 HU and produced 16432.81 kg ha^{-1} and 22680.45 kg ha^{-1}of dry matter in irrigated and non-irrigated conditions, respectively, at maturity. Meanwhile, the Mv 352 hybrid produced 23149.26 kg ha^{-1} and 20562.26 kg ha^{-1} in irrigated and non-irrigated conditions, respectively, at maturity, while accumulating 1315.34 HU. These results exceed 16190 kg ha^{-1}, i.e., the result obtained by Ferreira et al. (2023), and far exceed those found by Ravibabu et al. (2020). The only exception was that the results obtained by Ravibabu et al. (2020) exceeded those of the Fornad hybrid under irrigated conditions. At this stage, the kernels showed maximum accumulation under both treatments: 10073.05 kg ha^{-1} and 8973.09 kg ha^{-1} in Mv 352 and Fornad, respectively, under irrigated conditions, and 9760.24 kg ha^{-1} and 11916.45 kg ha^{-1} and 8973.09 kg ha^{-1} in Mv352 and Fornad, respectively, under non-irrigated conditions.

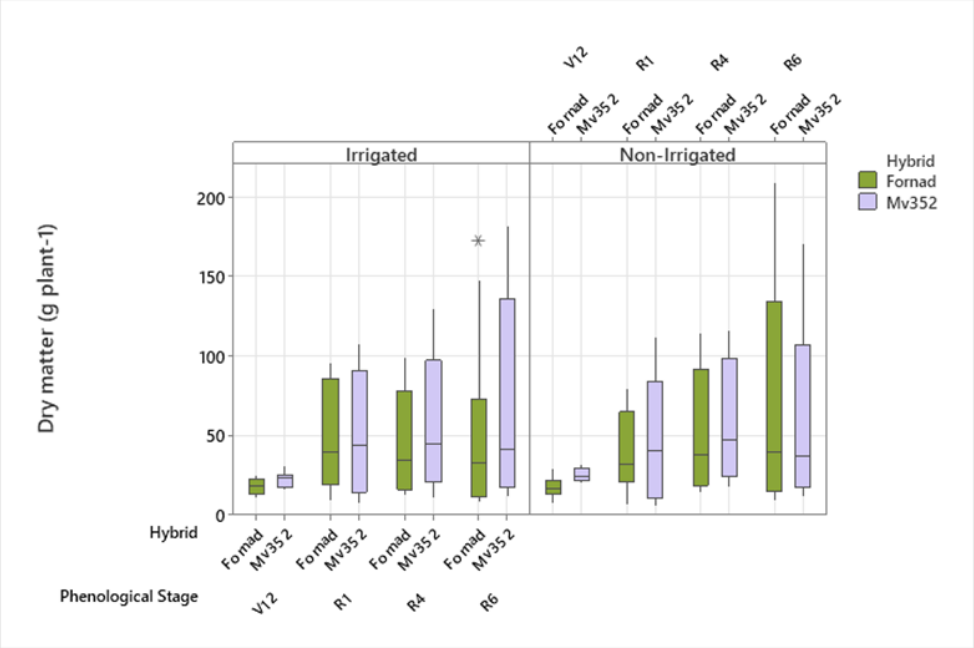

Figure 41. Dry matter uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Treatment: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2023).

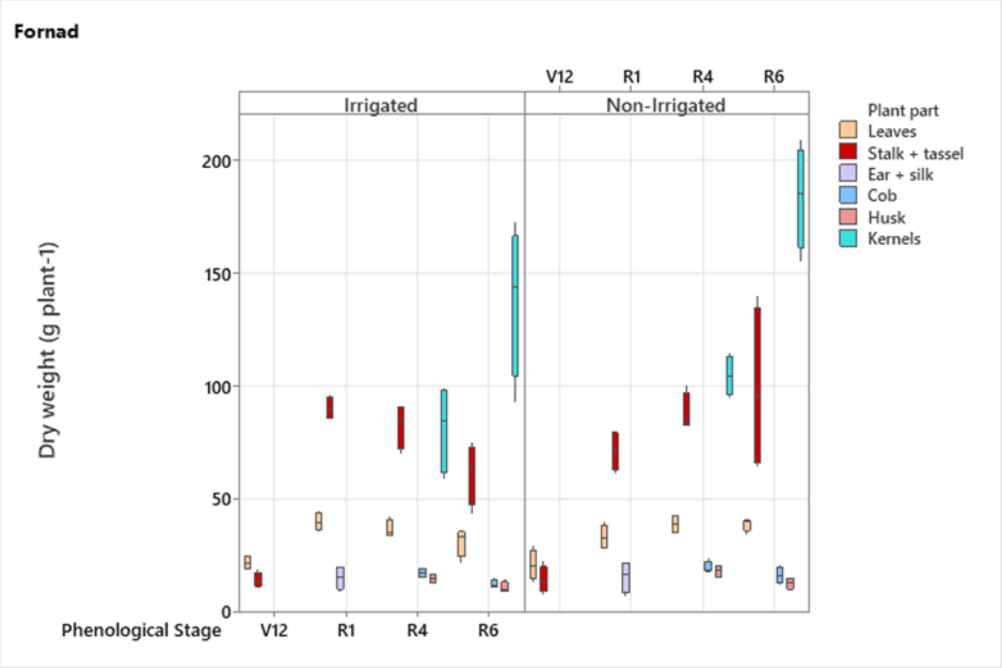

Figure 42. Dry matter accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Treatment: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2023).

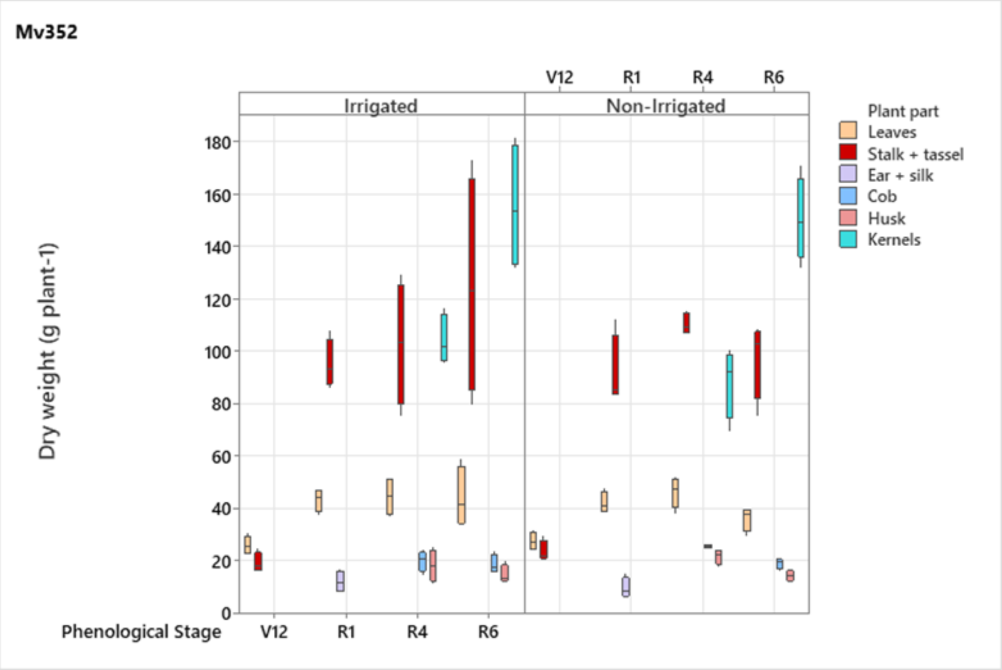

Figure 43. Dry matter accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Treatment: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2023).

The accumulation of nitrogen was significantly affected by treatment, phenological stage, plant part, and hybrid as well as the interaction of Hybrid*Plant Part. Irrigated plants, especially Mv 352 retained more N overall (Figure 44). Throughout the plant growth and development, N was mostly stored in vegetative organs, especially in leaves, until reaching R4, after which it shifted to the kernels (Figure 45, Figure 46).

At V12, under irrigation, maize had the first peak of N uptake in the vegetative parts during the active vegetative growth stage, accumulating 26.8% and 39.2% of the total N content in Mv 352 and Fornad, respectively. While, under non-irrigated conditions, their accumulations were 34.3% and 36.2%, respectively. By the time of silking, Mv 352 and Fornad had absorbed, respectively, 54.1% and 78.1% of total nitrogen content under irrigated conditions, and 52.8% and 50% under non-irrigated conditions. The maximum N accumulation was observed at R4 in the Fornad hybrid under irrigated conditions, with a total accumulation of 164.11 kg ha^{-1} of N, of which 64.94 kg ha^{-1} was accumulated by the kernels. However, this N accumulation in the kernels was the lowest of all the accumulated N concentrations among the hybrids and under both treatments. In contrast, the maximum N accumulation occured at R6 for Mv 352 under irrigated conditions and for both hybrids under non-irrigated conditions. At maturity stage, the maximum N accumulations were observed in the kernels at 174.47 kg ha^{-1} and 151.01 kg ha^{-1} for Mv 352 under irrigated and non-irrigated conditions and 104.41 kg ha^{-1} and 120.25kg ha^{-1} for Fornad under irrigated and non-irrigated conditions. This was followed by accumulation in the leaves at 47.32 kg ha^{-1} and 33.37 kg ha^{-1} for Mv 352 under irrigated and non-irrigated conditions and 22.66 kg ha^{-1} and 24.01 kg ha^{-1} for Fornad under irrigated and non-irrigated conditions. The accumulated N content by maize kernels was found to be equal to 63.4% and 68.5% in Mv 352 under irrigated and non-irrigated and 63.6% and 68.6% in Fornad. Similar studies have indicated values of approximately 64% (Bender et al., 2013), 53% (Silva et al., 2018)and, 74% (Ferreira et al., 2023).

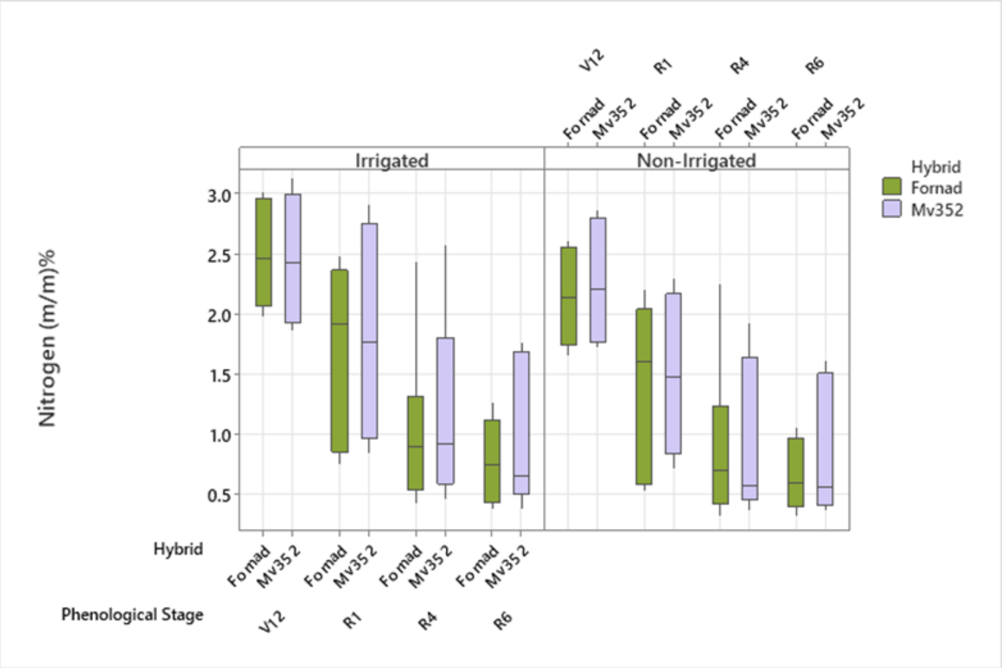

Figure 44. Nitrogen uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Treatment: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Plant part: $p<0.001$. (Debrecen, 2023).

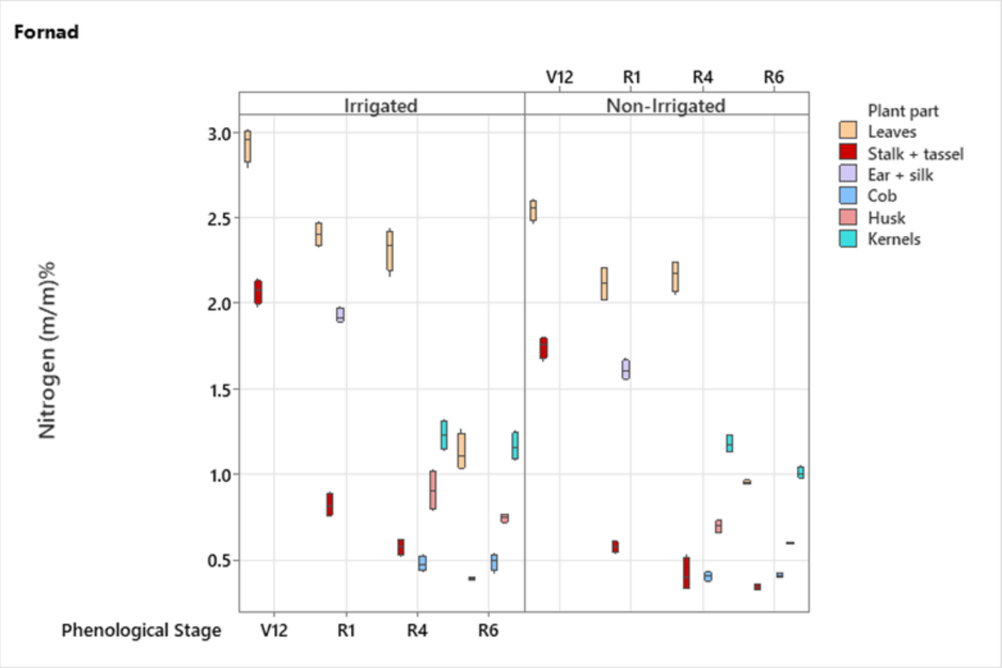

Figure 45. Nitrogen accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Treatment: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Plant part: $p<0.001$. (Debrecen, 2023).

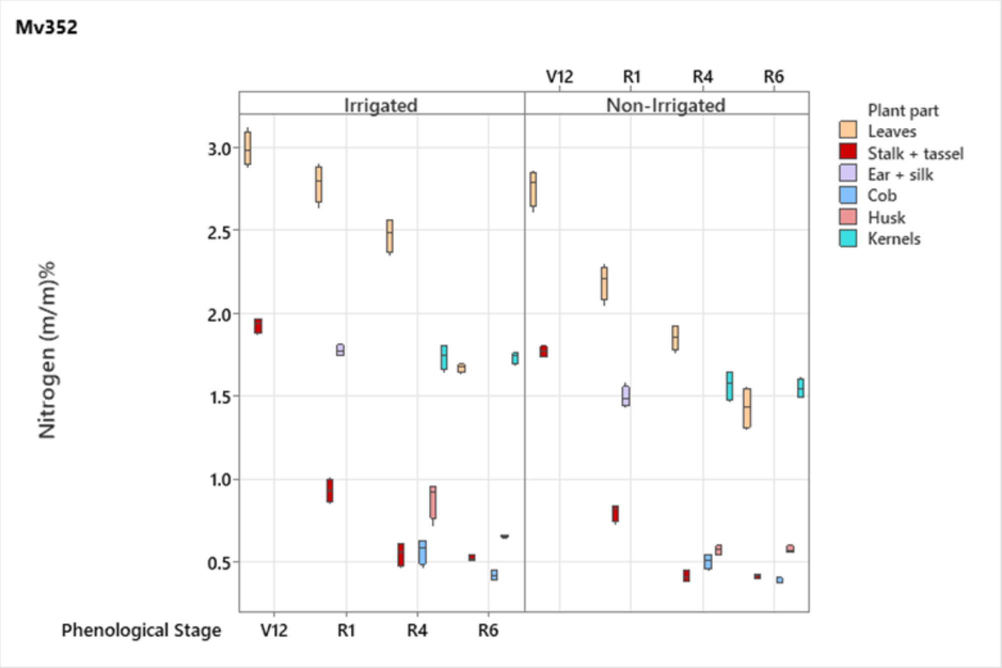

Figure 46. Nitrogen accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Treatment: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Plant part: $p<0.001$. (Debrecen, 2023).

Phosphorus was significantly influenced by treatment, phenological stage, plant part and Treatment*Phenological Stage interactions. Though hybrid did not differ significantly, Hybrid*Phenological stage and Hybrid*Plant part interactions were significant. Irrigated plants accumulated more P content (Figure 47). This pattern justify the strong P mobility and responsiveness to water status. At the end of the cycle, the kernels retained more P than other organs. Throughout the plant growth and development, P was mainly stored in plant vegetative organs, mostly in the leaves, until reaching R1, after which it shifted to the kernels (Figure 48, Figure 49). Prior to the silking stage, at V12, Mv 352 and Fornad accumulated 33.4% and 29.7% of the total P content, respectively, under irrigated conditions, and 43.3% and 22.7% of the total P uptake, respectively, under non-irrigated conditions. By the time of silking, Mv 352 and Fornad had absorbed 47.6% and 57.7% of the total phosphorus content, respectively, under irrigation, versus 55.5% and 39.4% without irrigation. These values are lower than the result obtained by Silva et al. (2018) (69%). The maximum P accumulation by the plants was established at R4 in the case of Fornad under irrigation, where it accumulated 43.58 kg ha^{-1} of total P concentrations, and in Mv 352 under non-irrigated conditions with 34.93 kg ha^{-1} of total P uptake. During the maturity stage, the total P accumulations in Mv 352 and Fornad were 48.55 kg ha^{-1} and 41.09 kg ha^{-1} under irrigation. While their accumulation under rainfed conditions were 32.87 kg ha^{-1} and 42.47 kg ha^{-1}. P uptake by the different plant organs is as follows: 32.96 kg ha^{-1} in the kernels, 7.55 kg ha^{-1} in the stalk, 6.65 kg ha^{-1} in the leaves, 0.799 kg ha^{-1} in the husk, and 0.581 kg ha^{-1} in the cob for Mv352 under irrigated conditions. Meanwhile, Fornad, under irrigation, accumulated 27.5 kg ha^{-1} in the kernels, 6.42 kg ha^{-1} in the stalk, 5.82 kg ha^{-1} in the leaves, 0.79 kg ha^{-1} in the husk, and 0.57 kg ha^{-1} in the cob. Under non-irrigated conditions, 26.05 kg ha^{-1} in the kernels, 2.98 kg ha^{-1} in the stalk, 2.85 kg ha^{-1} in the leaves, 0.542 kg ha^{-1} in the husk, and 0.449 kg ha^{-1} in the cob for Mv 352. While Fornad accumulated 30.36 kg ha^{-1} in the kernels, 6.99 kg ha^{-1} in the stalk, 3.92 kg ha^{-1} in the leaves, 0.65 kg ha^{-1} in the husk, and 0.55 kg ha^{-1} in the cob.

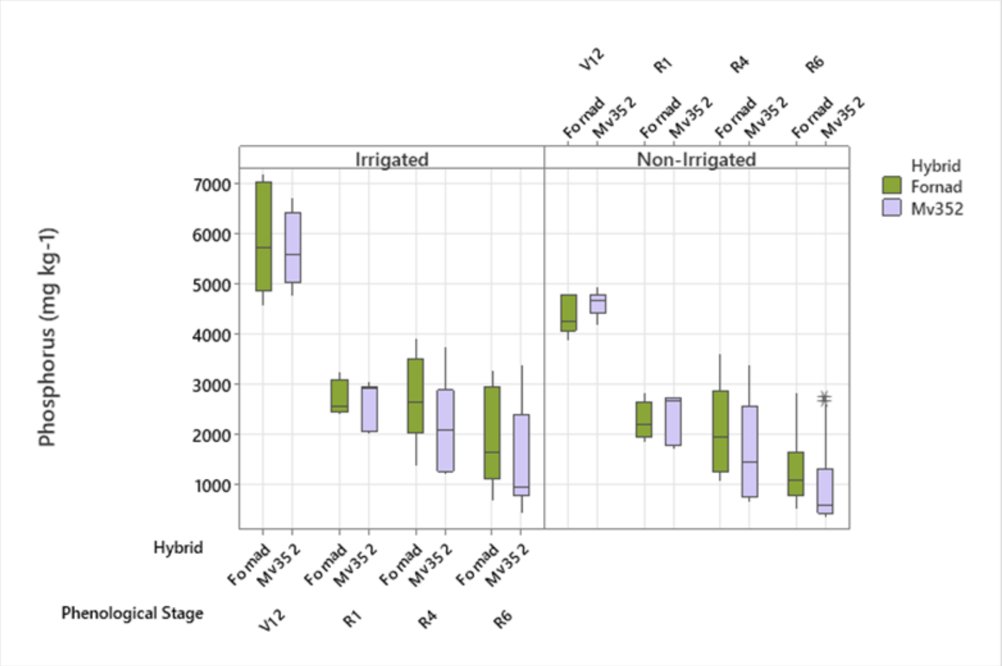

Figure 47. Phosphorus uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Treatment: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Phenological Stage: $p<0.01$, Treatment*Phenological Stage and Hybrid*Plant part: $p<0.001$. (Debrecen, 2023).

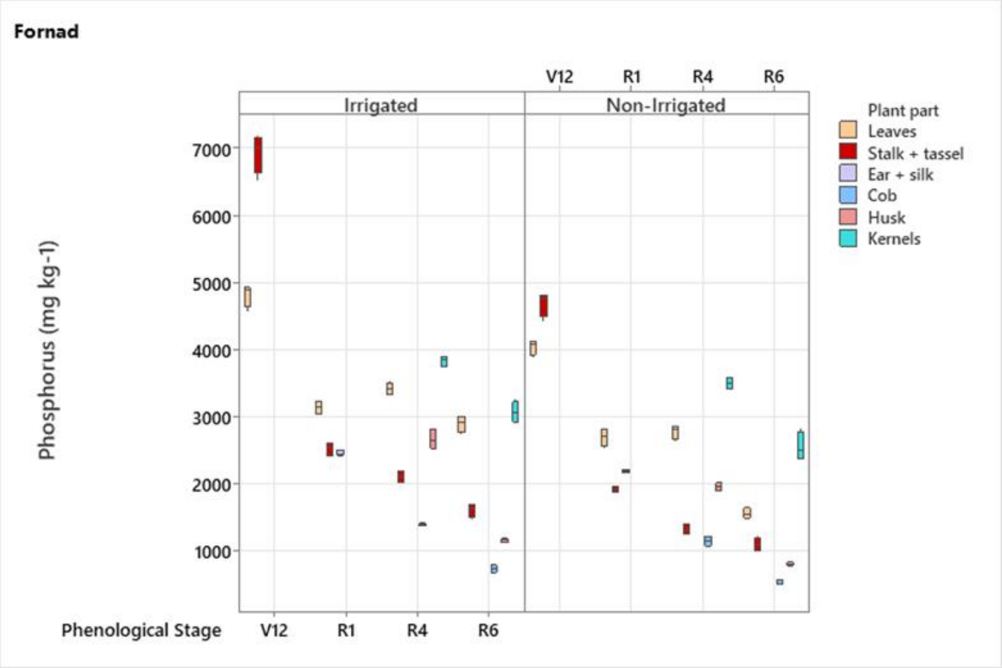

Figure 48. Phosphorus accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.01, Treatment*Phenological Stage and Hybrid*Plant part: p<0.001. (Debrecen, 2023).

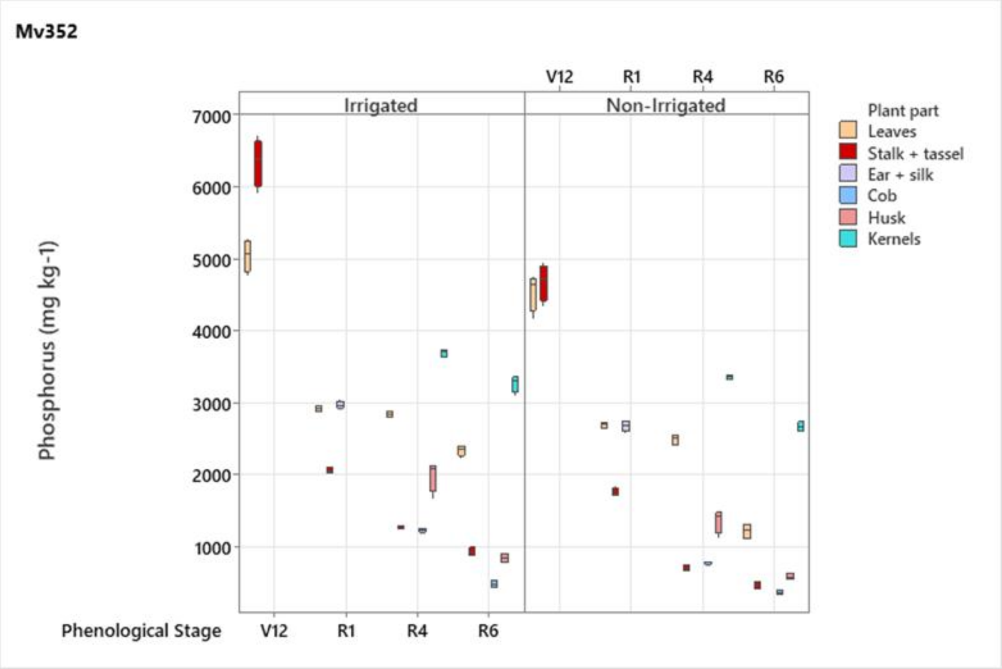

Figure 49. Phosphorus accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.01, Treatment*Phenological Stage and Hybrid*Plant part: p<0.001. (Debrecen, 2023).

Potassium was highly influenced by treatment (p<0.05), phenological stage and plant part (p<0.001). Potassium contents were significantly higher in irrigated plants, especially in stalk+tassel and at the early stage (V12) (Figure 50). K is the early mobile and plays a major role in water regulation, which likely explains its sensitivity. Its accumulation at V12 was significant, accumulating in Mv 352 and Fornad 215.69 kg ha^{-1} and 197.97 kg ha^{-1} of the total potassium content, respectively (Figure 51, Figure 52). Interestingly, maize had achieved its maximum K accumulation at the silking stage in Mv 352 (321.76 kg ha^{-1}) and Fornad (287.05 kg ha^{-1}) under irrigated conditions, and in Mv 352 (262.68 kg ha^{-1}) under non-irrigated conditions. Meanwhile, Fornad's maximum K uptake (213.63 kg ha^{-1}) was obtained at R4 under non-irrigated conditions. At R4, Mv 352 absorbed 155.1 kg ha^{-1} in the stalk, 62.34 kg ha^{-1} in the leaves, 41.88 kg ha^{-1} in the kernels, 12.36 kg ha^{-1} in the husk, and 9.93 kg ha^{-1} in the cob, totaling 281.61 kg ha^{-1} under irrigated conditions. Meanwhile, under non-irrigated conditions, this hybrid accumulated 102.69 kg ha^{-1} in the stalk, 54.85 kg ha^{-1} in the leaves, 34.29 kg ha^{-1} in the kernels, 13.88 kg ha^{-1} in the husk, and 9.04 kg ha^{-1} in the cob, totaling 214.74 kg ha^{-1}. Fornad, on the other hand, accumulated under irrigated conditions, 140.78 kg ha^{-1} in the stalk, 54.42 kg ha^{-1} in the leaves, 32.92 kg ha^{-1} in the kernels, 11.03 kg ha^{-1} in the husk, and 8.9 kg ha^{-1} in the cob, totaling 248.05 kg ha^{-1}. While its accumulation under non-irrigated conditions was 106.7 kg ha^{-1} in the stalk, 50.56 kg ha^{-1} in the leaves, 37.24 kg ha^{-1} in the kernels, 11.62 kg ha^{-1} in the husk, and 7.50 kg ha^{-1} in the cob, totaling 248.05 kg ha^{-1}. Throughout the growing season, the stalk was the main K reservoir. This indicates that the extent of K remobilization was highest in the stalk, suggesting that K was primarily remobilized from the stalk rather than the leaves. Furthermore, we observed that the extent of potassium translocation from the stalk and leaves to the kernels was notably lower than that of phosphorus and nitrogen. This was at a rate of 10.3% for Mv 352 and Fornad under irrigation and 10.1% for Mv 352 and 15.8% for Fornad under non-irrigation of the total K at maturity. At R6, Mv 352 absorbed 219.98 kg ha^{-1} in the stalk, 43.40 kg ha^{-1} in the leaves, 33.03 kg ha^{-1} in the kernels, 13.01 kg ha^{-1} in the husk, and 6.1 kg ha^{-1} in the cob, totaling 315.5 kg ha^{-1} under irrigated conditions. Meanwhile, under non-irrigated conditions, this hybrid accumulated 131.5 kg ha^{-1} in the stalk, 31.6 kg ha^{-1} in the leaves, 26.63 kg ha^{-1} in the kernels, 9.49 kg ha^{-1} in the husk, and 4.35 kg ha^{-1} in the cob, totaling 203.59 kg ha^{-1}. Fornad, on the other hand, accumulated under irrigated conditions 80.43 kg ha^{-1} in the stalk, 30.03 kg ha^{-1} in the leaves, 29.58 kg ha^{-1} in the kernels, 3.48 kg ha^{-1} in the husk, and 5.36 kg ha^{-1} in the cob, totaling 148.89 kg ha^{-1}. While its accumulation under non-irrigated conditions was 102.82 kg ha^{-1} in the stalk, 29.30 kg ha^{-1} in the leaves, 33.75 kg ha^{-1} in the kernels, 3.25 kg ha^{-1} in the husk, and 6.91 kg ha^{-1} in the cob, totaling 176.04 kg ha^{-1}.

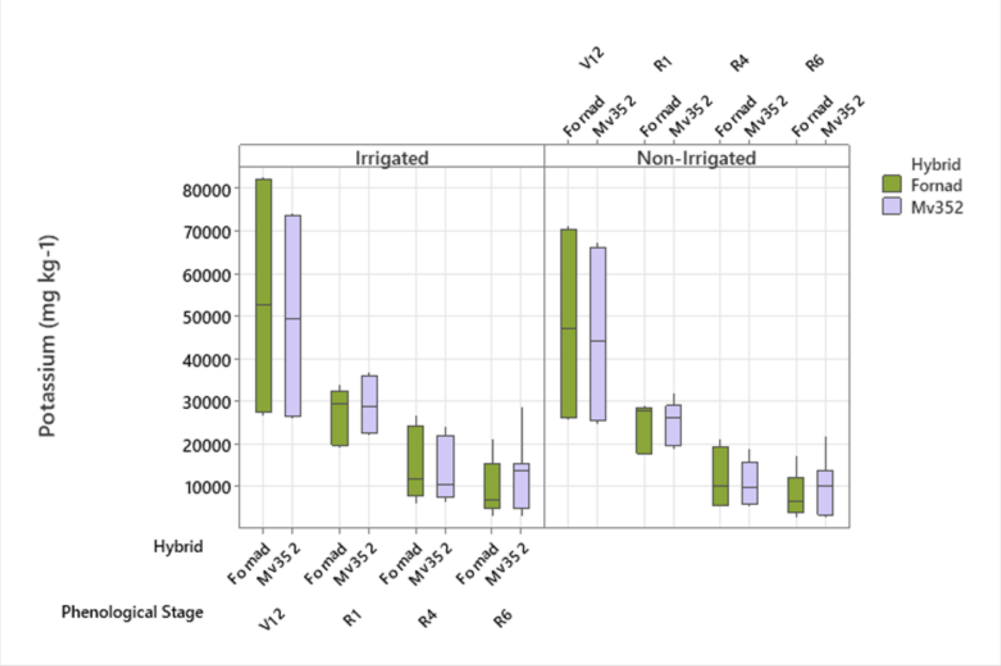

Figure 50. Potassium uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.05 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

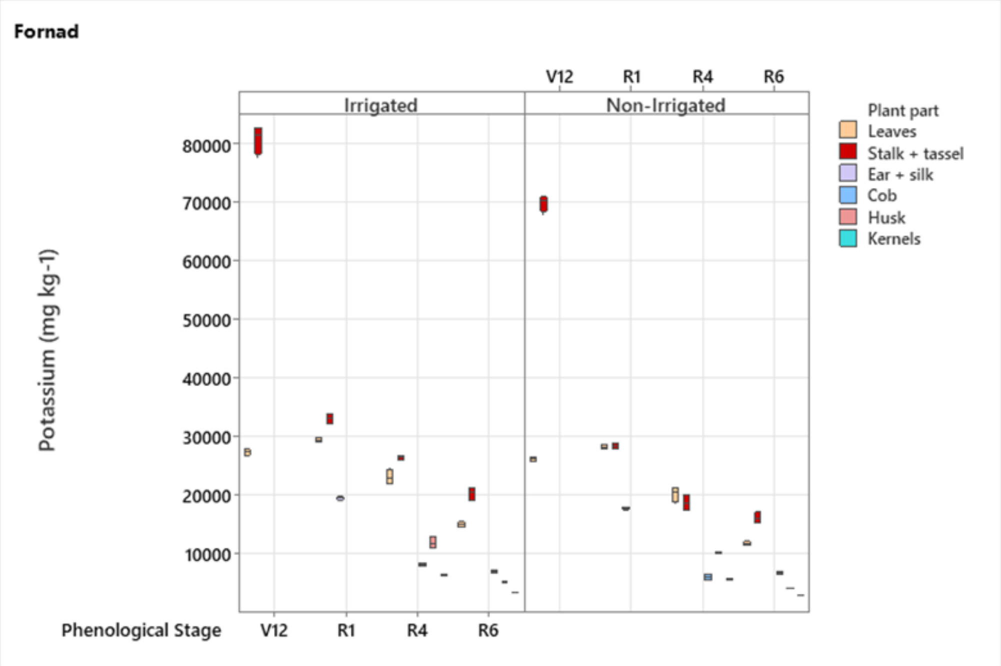

Figure 51. Potassium accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.05 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

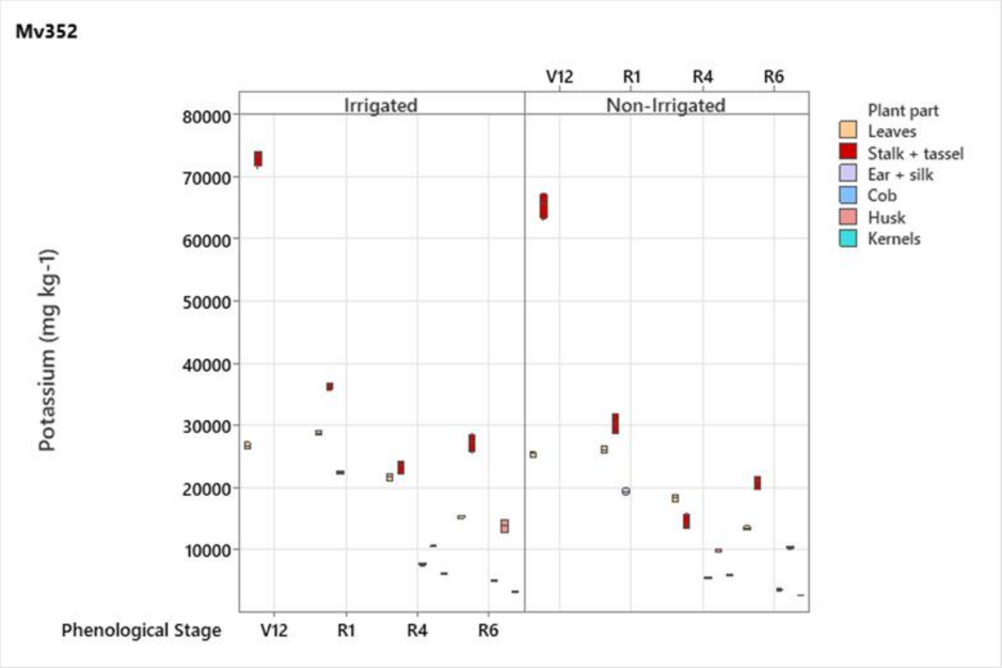

Figure 52. Potassium accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Treatment: $p<0.05$ | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2023).

Calcium was influenced by phenological stage, hybrid and plant part ($p<0.001$). It showed high accumulation in structural tissues such as leaves and stalk+tassel regardless of treatment. Fornad hybrid had significantly higher Ca accumulation. As a poorly mobile element, Ca was less sensitive to drought stress but highly tissue type-dependent (Figure 53). At V12, the total Ca accumulation in Mv 352 and Fornad, respectively, was 24.5% and 30% under irrigated conditions and 34.6% and 23.7% under non-irrigated conditions (Figure 54, Figure 55). Throughout the growing season, calcium was primarily absorbed by the leaves. Interestingly, by the time of silking, the Fornad hybrid had achieved its maximum calcium accumulation with 54.35 kg ha^{-1} under irrigated conditions. Under non-irrigation, it had achieved its maximum accumulation of calcium uptake at R6 as Mv 352. At R6, the highest Ca accumulations were observed in the leaves, followed by the stalks and then the kernels. For instance, Mv 352 absorbed 32.95 kg ha^{-1} in the leaves, 24.84 kg ha^{-1} in the stalk, 6.95 kg ha^{-1} in the kernels, 1.76 kg ha^{-1} in the husk, and 1.054 kg ha^{-1} in the cob, totaling 67.540 kg ha^{-1} under irrigated conditions. Meanwhile, under non-irrigated conditions, this hybrid accumulated 24.97 kg ha^{-1} in the leaves, 17.13 kg ha^{-1} in the stalk, 4.87 kg ha^{-1} in the kernels, 1.49 kg ha^{-1} in the husk, and 0.85 kg ha^{-1} in the cob, totaling 49.320 kg ha^{-1}. Fornad, on the other hand, accumulated under irrigated conditions 24.61 kg ha^{-1} in the leaves, 16.19 kg ha^{-1} in the stalk, 6.66 kg ha^{-1} in the kernels, 1.86 kg ha^{-1} in the husk, and 0.66 kg ha^{-1} in the cob, totaling 49.97 kg ha^{-1}. While its accumulation under non-irrigated conditions was 27.45 kg ha^{-1} in the leaves, 25.51 kg ha^{-1} in the stalk, 7.86 kg ha^{-1} in the kernels, 1.89 kg ha^{-1} in the husk, and 0.69 kg ha^{-1} in the cob, totaling 63.40 kg ha^{-1}.

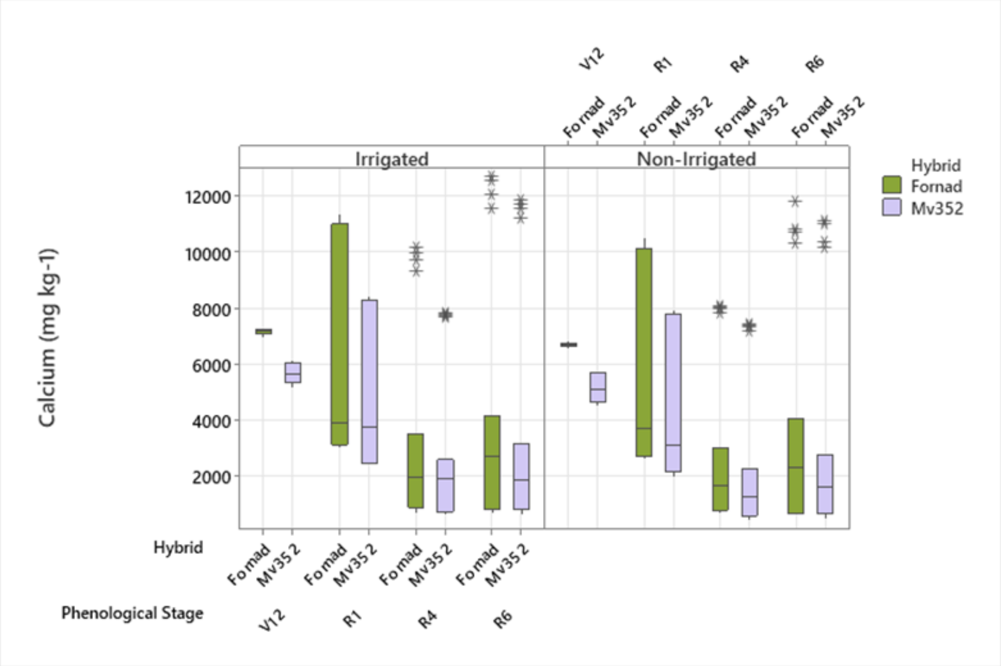

Figure 53. Calcium uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: ns | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

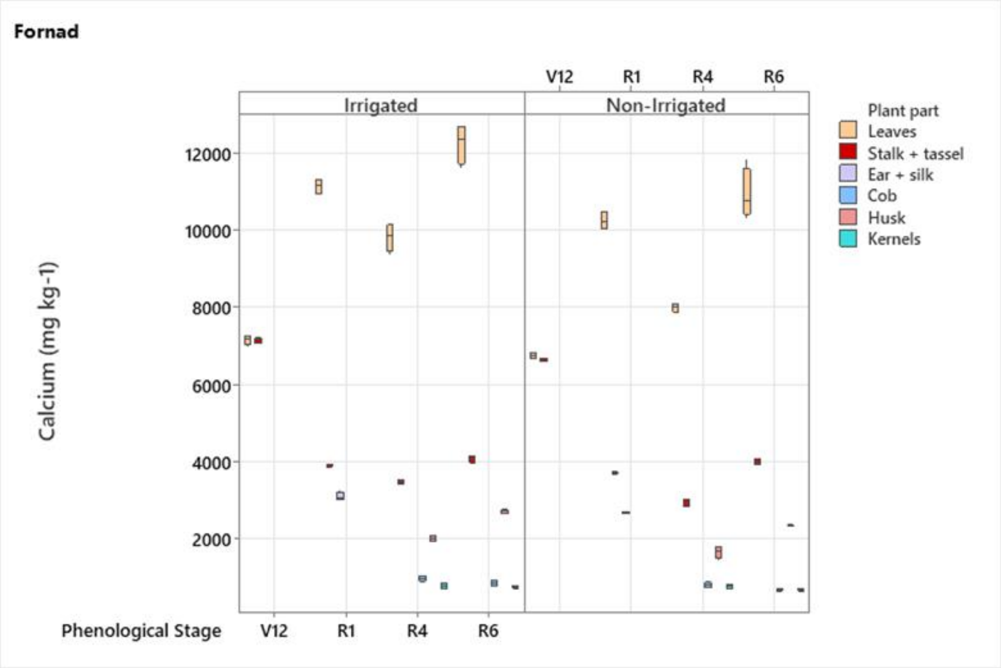

Figure 54. Calcium accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: ns | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

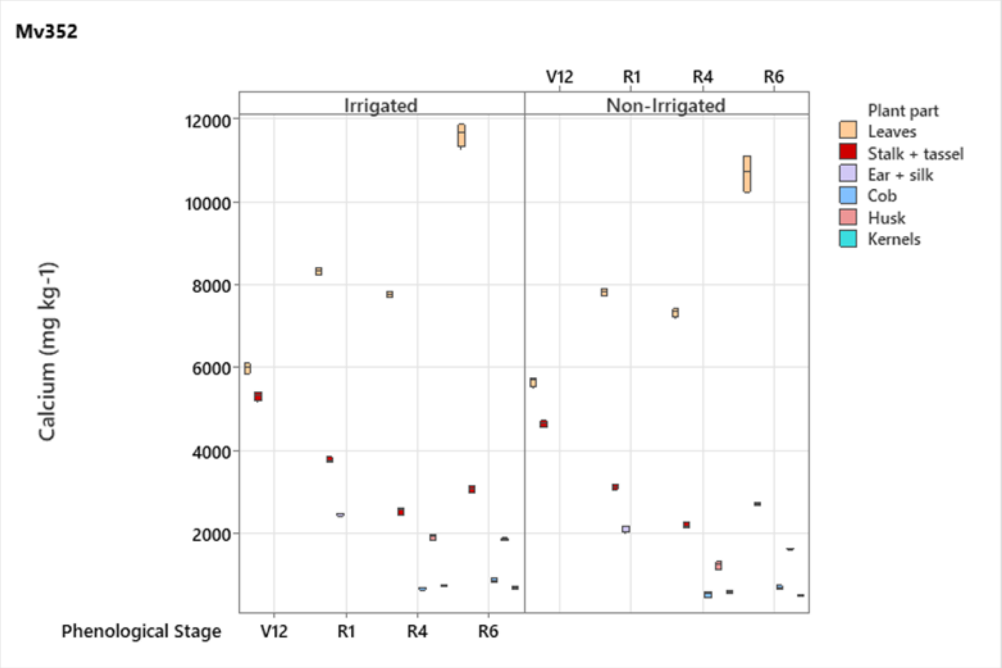

Figure 55. Calcium accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.001$ | Treatment: ns | Plant Part: $p<0.001$ | Interactions: ns. (Debrecen, 2023).

Magnesium content was greatly influenced by phenological stage, plant part and treatment ($p<0.001$), and hybrid ($p<0.01$). Treatment*Plant part was also significant. Magnesium was considerably lower in non-irrigated plants (Figure 56). The highest accumulation of magnesium was found in leaves or stalks, indicating their role in chlorophyll and remobilization. Fornad was found to retain more Mg than Mv 352. At V12, the total Mg accumulation for irrigated plants was 17% in Mv 352 and 21.5% in Fornad, and 23.7% and 14.2% for non-irrigated plants, respectively. Reaching R1, Mv 352 and Fornad accumulated 49.4% and 70.2% of the total Fe accumulation with irrigation, compared to 55.5% and 40.6% without irrigation (Figure 57, Figure 58). Interestingly, by the time of R4, the Fornad hybrid had achieved its maximum magnesium accumulation of 23.26 kg ha^{-1} under irrigated conditions. Meanwhile, the same hybrid achieved its Mg accumulation under non-irrigated conditions at R6 with 28.92 kg ha^{-1}. Mv 352, on the other hand, accumulated its maximum magnesium content at R6 with 33.17 kg ha^{-1} under irrigated conditions, and 24.67 kg ha^{-1} without irrigation. Reaching R6, Mv 352 absorbed 14.01 kg ha^{-1} in the kernels, 10.83 kg ha^{-1} in the stalk, 6.98 kg ha^{-1} in the leaves, 0.846 kg ha^{-1} in the husk, and 0.5 kg ha^{-1} in the cob, totaling 33.17 kg ha^{-1} under irrigated conditions. Meanwhile, under non-irrigated conditions, this hybrid accumulated 13.340 kg ha^{-1} in the kernels, 5.823 kg ha^{-1} in the stalk, 4.425 kg ha^{-1} in the leaves, 0.605 kg ha^{-1} in the husk, and 0.474 kg ha^{-1} in the cob, totaling 24.67 kg ha^{-1}. Fornad, on the other hand, accumulated under irrigated conditions 11.05 kg ha^{-1} in the kernels, 6.084 kg ha^{-1} in the stalk, 4.456 kg ha^{-1} in the leaves, 0.733 kg ha^{-1} in the husk, and 0.368 kg ha^{-1} in the cob, totaling 22.69 kg ha^{-1}. While its accumulation under non-irrigated conditions was 14.581 kg ha^{-1} in the kernels, 8.111 kg ha^{-1} in the stalk, 5.049 kg ha^{-1} in the leaves, 0.782 kg ha^{-1} in the husk, and 0.395 kg ha^{-1} in the cob, totaling 28.919 kg ha^{-1}.

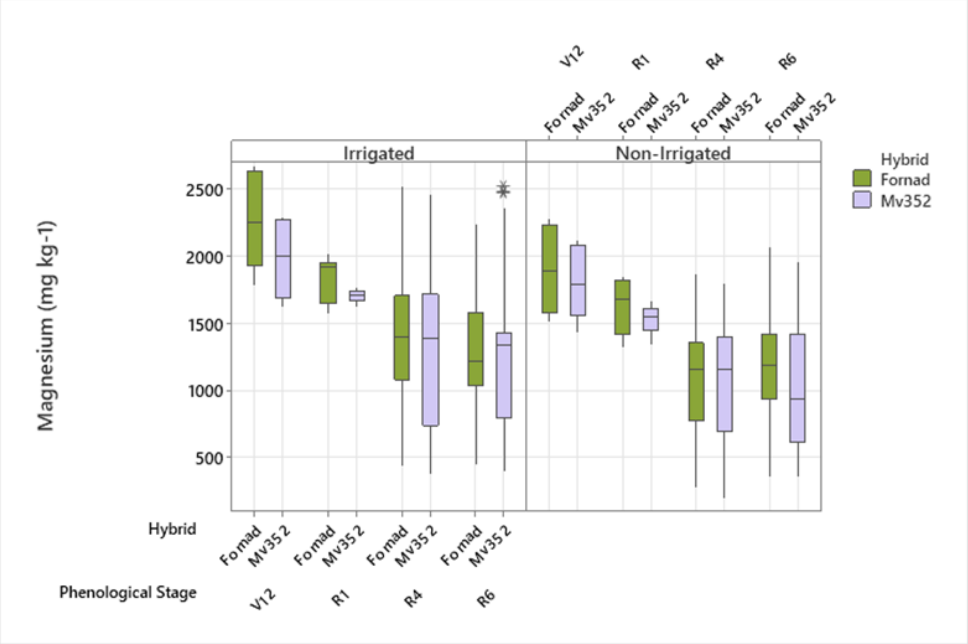

Figure 56. Magnesium uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Treatment*Plant Part: p<0.01. (Debrecen, 2023).

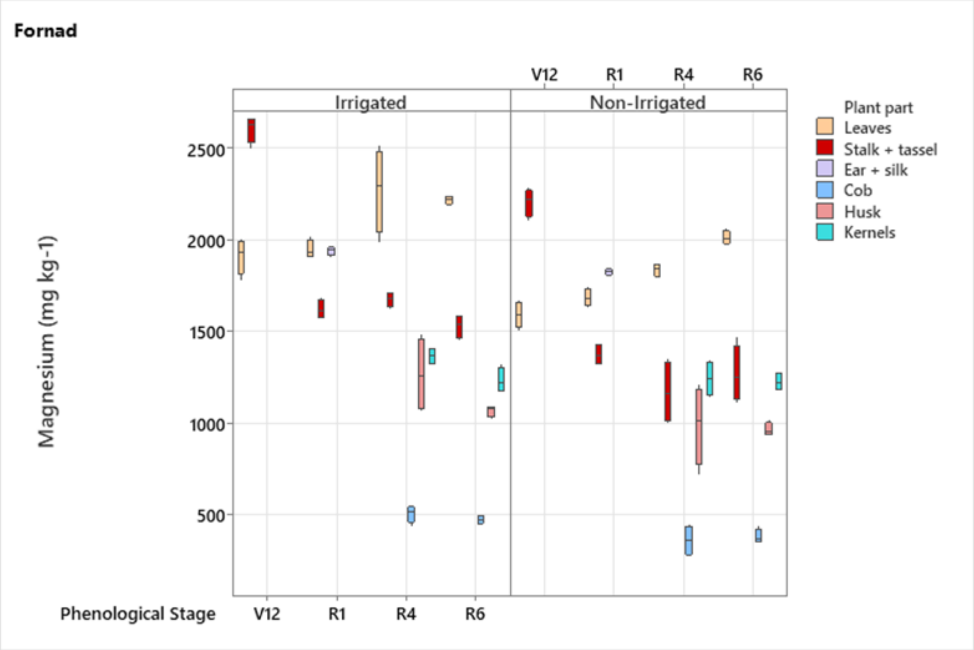

Figure 57. Magnesium accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Treatment*Plant part: p<0.01.

(Debrecen, 2023).

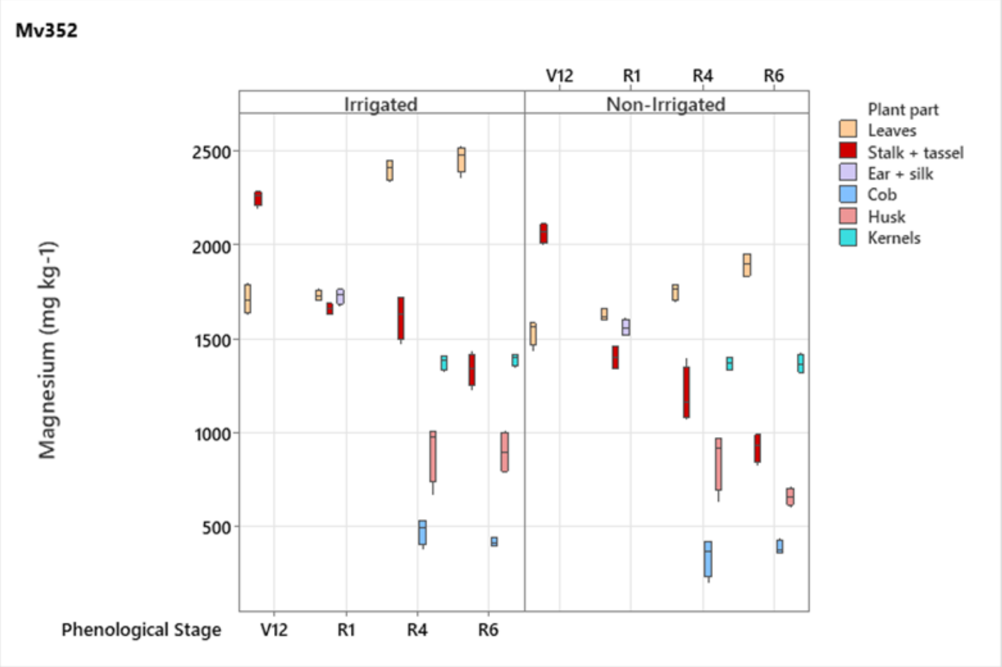

Figure 58. Magnesium accumulation within Mv 352 hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.01$ | Treatment: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Treatment*Plant part: $p<0.01$. (Debrecen, 2023).

Sulfur uptake was significantly influenced by phenological stage, plant part and treatment ($p<0.001$). Its accumulation was substantially greater in irrigated treatment ($p<0.001$), particularly in Fornad even though it was not significant (Figure 59). Sulfur concentrated mainly in leaves, and then in kernels, indicating translocation (Figure 60, Figure 61). Its mobility and drought response were similar to nitrogen. At V12, Mv 352 absorbed 36.3% of the total amount of S taken up, while Fornad absorbed 34.9%, under irrigation. Similarly, Mv 352 accumulated 40.1% without irrigation, whereas Fornad accumulated 27.6% of the total S uptake. While, at R1, Mv 352 accumulated under irrigation and non-irrigation, respectively, 77.2% and 70% of the total S uptake. Fornad, on the other hand, absorbed 79.8% and 54.2% of the total amount of S taken up under irrigation and non-irrigation. By the time of R4, both hybrids had maximized their S accumulation. At this stage, Mv 352 had accumulated 16.99 kg ha^{-1} and 15.64 kg ha^{-1} under irrigated and non-irrigated conditions, respectively. Meanwhile, Fornad accumulated 14.73 kg ha^{-1} and 16.01 kg ha^{-1} under irrigated and non-irrigated conditions, respectively. At maturity, Mv 352 absorbed 9.106 kg ha^{-1} in the kernels, 3.29 kg ha^{-1} in the leaves, 2.67 kg ha^{-1} in the stalk, 0.37 kg ha^{-1} in the husks, and 0.322 kg ha^{-1} in the cobs, totaling 15.76 kg ha^{-1}

under irrigated conditions. Meanwhile, under non-irrigated conditions, the same hybrid accumulated 7.801 kg ha^{-1} in the kernels, 1.5729 kg ha^{-1} in the stalk, 1.5728 kg ha^{-1} in the leaves, 0.308 kg ha^{-1} in the husk, and 0.22 kg ha^{-1} in the cob, totaling 11.474 kg ha^{-1}. In contrast, Fornad accumulated 7.347 kg ha^{-1} in the kernels, 2.039 kg ha^{-1} in the leaves, 1.407 kg ha^{-1} in the stalk, 0.302 kg ha^{-1} in the husk, and 0.280 kg ha^{-1} in the cob under irrigated conditions, totaling 11.374 kg ha^{-1}. Meanwhile, its accumulation under non-irrigated conditions was 8.837 kg ha^{-1} in the kernels, 2.021 kg ha^{-1} in the stalk, 1.884 kg ha^{-1} in the leaves, 0.321 in the husk, and 0.26 kg ha^{-1} in the cob, totaling 13.322 kg ha^{-1}.

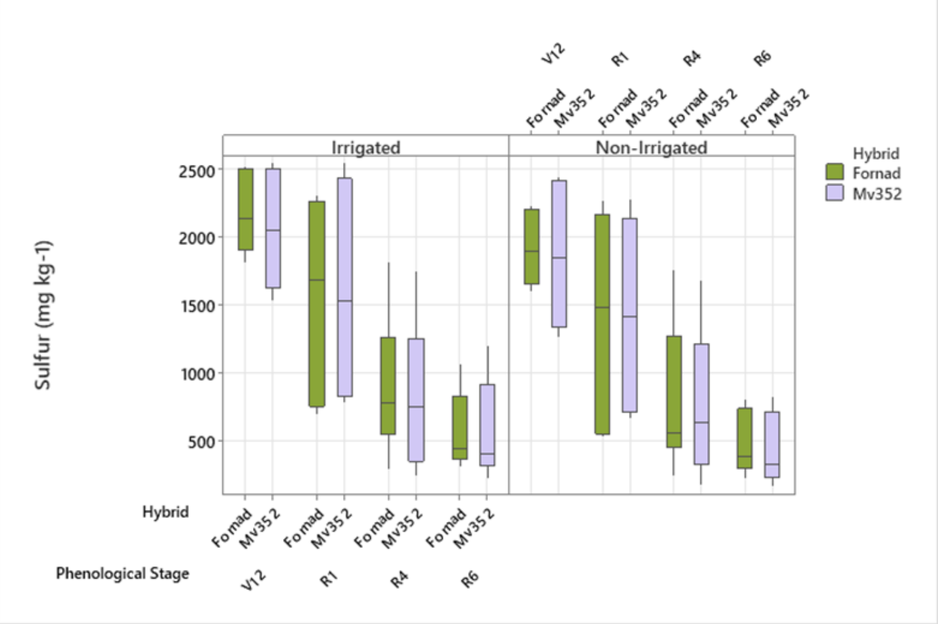

Figure 59. Sulfur uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

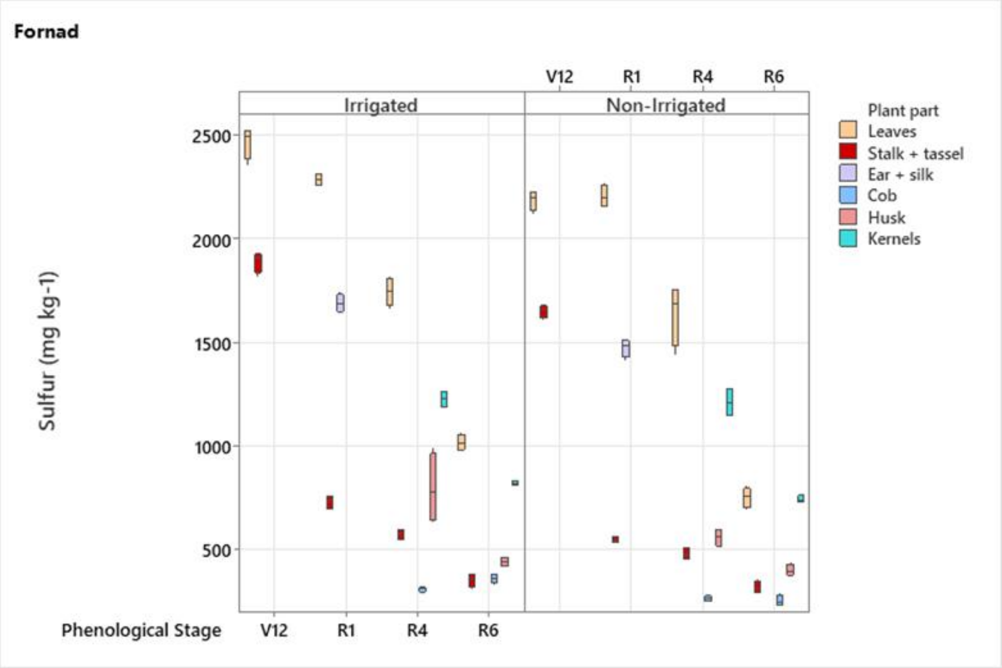

Figure 60. Sulfur accumulation within Fornad hybrid as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

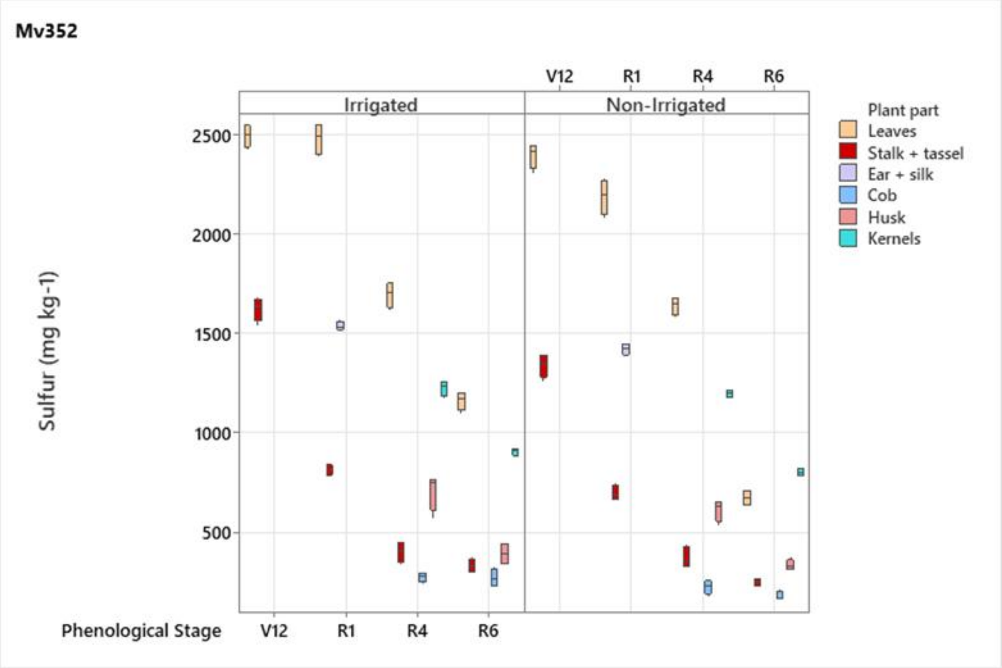

Figure 61. Sulfur accumulation within Mv 352 as a function of phenological stages under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

Iron accumulation was significantly affected by plant part and water treatment (p<0.001), with key interaction effects of Hybrid*Phenological Stage, Treatment*Plant Part and Hybrid*Plant Part. Mv 352 consistently accumulated more iron in its leaves, while Fornad shifted iron between its leaves and stalks. Irrigation had increased Fe uptake. At V12, irrigated plants accumulated 26.6% and 27.1%

(Mv 352 and Fornad, respectively) versus 32.1% and 29.1% in the non-irrigation plot (Appendix 3 and 4). At R1, irrigated plants of Mv 352 and Fornad reached 62.4% and 76.7% versus 65.5% and 57.5% under non-irrigation. The maximum Fe content was reached at R4 in Fornad (1.63 kg ha^{-1} with irrigation vs. 1.37 kg ha^{-1} without irrigation) and at while Mv 352 reached its peak at R6 with 2.144 kg ha^{-1} with irrigation vs. 1.424 kg ha^{-1} at R4 without irrigation. At R6, under irrigation, Fornad reached a total of 0.897 kg ha^{-1} and 1.151 kg ha^{-1} without irrigation, while Mv 352 absorbed 1.225 kg ha^{-1} without irrigation. Boron on the other hand, was influenced by stage and part ($p<0.001$), and by treatment ($p<0.01$) and Hybrid*Phenological Stage ($p<0.05$). Irrigated plants significantly accumulated more B, particularly in the leaves at V12. At V12, irrigated plants accumulated 21.3% (Mv 352) and 37% (Fornad) versus 35.5% (Mv 352) and 29.1% (Fornad) in the absence of irrigation (Appendix 3 and 4). At silking, irrigated plants absorbed 39.4% (Mv 352) and 77.3% (Fornad) versus 50.3% (Mv 352) and 45% (Fornad). The maximum concentration of boron occurred at R6, observed particularly in leaves and then kernels with the exception of exception Mv352 under irrigation, where the stalk accumulated more boron. For instance, totals of 0.150 kg ha^{-1} under irrigation and 0.093 kg ha^{-1} under non-irrigation for Mv 352 and 0.078 kg ha^{-1} under irrigation and 0.085 kg ha^{-1} under non irrigation for Fornad. Copper, on the other hand, was influenced by phenological stage, treatment and plant part ($p<0.001$) but not by hybrid, and with all interactions except Treatment*Hybrid being significant. Irrigation strongly increased Cu accumulation. At V12, the uptake of irrigated plants was 4.9% (Mv 352) and 5.2% (Fornad) versus 10.4% (Mv 352) and 12.7% (Fornad) for non-irrigated plants (Appendix 3 and 4). At R1, irrigated plants accumulated 9.5% (Mv 352) and 12.4% (Fornad) versus 15.2% (Mv 352) and 21.1% (Fornad) without irrigation. At R6, Mv 352 reached 0.450 kg ha^{-1} under irrigation and 0.225 kg ha^{-1} under non-irrigation, while Fornad reached 0.307 kg ha^{-1} with irrigation and 0.116 kg ha^{-1} without irrigation. Similarly, Mn accumulation was also affected by phenological stage and plant part ($p<0.001$), as well as by hybrid and treatment ($p<0.05$), with significant interactions. Mv 352 accumulated more Mn overall. It was found that leaves accumulated a maximum of manganese content and water stress reduced Mn accumulation. At V12, irrigated plants absorbed 43.7% (Mv 352) versus 28.7% (Fornad) and 55.9% (Mv 352) versus 26% (Fornad) without irrigation (Appendix 3 and 4). While, at R1, Mv 352 accumulated under irrigation and non-irrigation, respectively, 75.2% and 83% of the total Mn uptake. Fornad, on the other hand, absorbed 83.9% and 58.7% of the total amount of Mn taken up under irrigation and non-irrigation. By the time of R4, the Fornad hybrid had achieved its maximum Mn accumulation of 0.558 kg ha^{-1} under irrigated conditions. Meanwhile, the same hybrid achieved its Mn accumulation under non-irrigated conditions at R6 with 0.551 kg ha^{-1}. Mv 352, on the other hand, accumulated its maximum Mn content at R6 with 0.688 kg ha^{-1} under irrigated conditions, and at R4 with 0.498 kg ha^{-1} without irrigation. At R6, Mv 352 and Fornad absorbed 0.688 kg ha^{-1} and 0.517 kg ha^{-1} with irrigation and 0.477 kg ha^{-1} and 0.551 kg ha^{-1} without irrigation, respectively. Lastly, Zn accumulation was influenced by phenological stage, treatment, hybrid and plant part ($p<0.001$), with higher levels observed under irrigation. Fornad significantly accumulated higher Zn content compared to Mv 352. At V12, irrigated plants absorbed 22.6% (Mv 352) versus 19.8% (Fornad) and 29.5% (Mv 352) versus 19.2% (Fornad) without irrigation (Appendix 3 and 4). At R1, irrigated plants absorbed 55.7% (Mv 352) versus 64.2% (Fornad) and 63.2% (Mv 352) versus 46.9% (Fornad) without irrigation. Mv 352 hybrid reached its maximum accumulation at R4 with 0.228 kg ha^{-1} under non-irrigated conditions.At R6, Zn accumulation by irrigated plants totaled 0.306 kg ha^{-1} in Mv 352 and 0.287 kg ha^{-1} in Fornad. Meanwhile, without irrigation, these hybrids absorbed 0.195 kg ha^{-1} (Mv 352) and 0.272 kg ha^{-1} (Fornad) of the total zinc.

- Plant height in 2023 under irrigated and rainfed conditions

The plant height of maize hybrids significatly varried throught the different growth stages ($p<0.001$), and among the hybrids ($p<0.001$). For instance, Mv 352 was taller than Fornad (Figure 62). Additionally, maize plant height was significantly greater in irrigated conditions. This finding is supported by Rasool et al. (2020), who found that plant height increases significantly with increasing irrigation water quantity. Likewise, it was reported by Gu et al. (2021) that a medium quantity of irrigation produced improvements in plant height of 13.8% and 10.8% at the filling stage and 12.9% and 10.7% at the maturity stage, compared to lower and higher quantities of irrigation. The variation was statistically significant between the plant height reached at early growth V12 and the later stages (Figure 63). The findings confirm irrigation potential to support vegetative growth. The maximum height the plant reached was at R4.

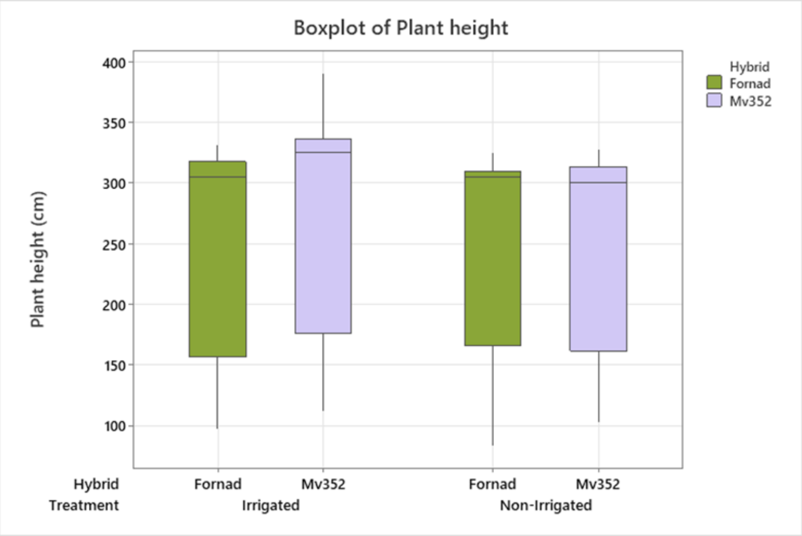

Figure 62. Plant height of maize under irrigated and rainfed conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Treatment*Hybrid: p<0.01. (Debrecen, 2023).

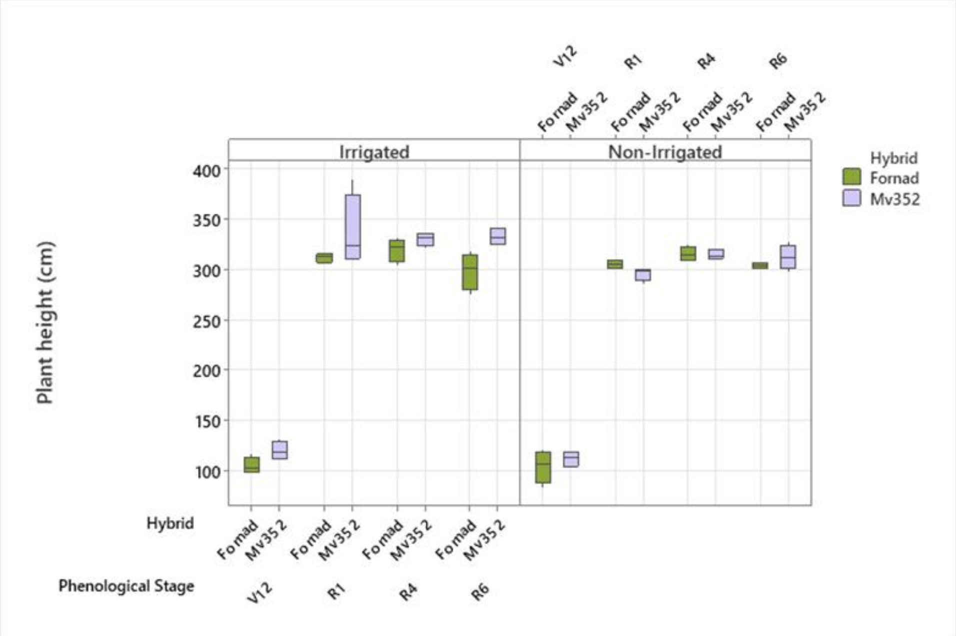

Figure 63. Plant height of maize as a function of phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Treatment*Hybrid: p<0.01. (Debrecen, 2023).

4.2.2 Correlation analysis of yield and the accumulated nutrient in maize under irrigated and non-irrigated conditions, 2023

Under irrigated conditions, the yield of Fornad was strongly linked to magnesium, moderately linked to potassium, boron, phosphorus, and sulfur, and positively correlated with calcium, with a negligible effect (Table 6). These correlations suggest efficient photosynthesis and kernel development processes, as well as good chlorophyll content and tolerance to oxidative stress. However, strong and moderate negative correlations were observed between yield and copper, zinc, and iron. By contrast, Mv 352's productivity continued to depend heavily on nitrogen, phosphorus, potassium, magnesium, and sulfur, consistent with its yield performance focused on physiology. The increasing correlation of sulfur implies improved potential for protein synthesis. However, there were shifts towards negative correlations in copper, iron, manganese, and zinc. Calcium and boron also demonstrated slight or negligible positive correlations. However, under non-irrigated conditions, Fornad's yield was maintained through the efficient use of nitrogen and phosphorus, and to a lesser extent, potassium (which are important for grain development and filling) (Table 6). There was a moderate association between magnesium and yield, indicating that its presence supports the maintenance of metabolic and photosynthetic functions. Conversely, boron, calcium, and sulfur exhibited strong negative correlations with Fornad's yield. Additionally, copper, manganese, zinc, and iron exhibited moderately to slightly negative correlations with yield. The Mv 352 hybrid exhibited strong positive correlations with iron and manganese and moderate positive correlations with copper and zinc with regard to yield. However, the rest of the examined accumulated nutrients displayed moderate to small negative correlations with yield.

Table 6. Correlations between maize yields and nutrient uptake under irrigated and non-irrigated conditions. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p<0.05$. (Debrecen, 2023).

	Fornad irrigated	**Fornad non-irrigated**	**Mv 352 irrigated**	**Mv 352 non-irrigated**
Nitrogen	-0.06	0.45	**0.84**	-0.52
Phosphorus	0.4	0.45	**0.95**	-0.49
Potassium	0.51	0.12	**0.79**	-0.03
Boron	0.47	-0.96	0.1	-0.18
Calcium	0.01	-0.79	0.03	-0.15
Copper	-0.88	-0.33	-0.49	0.48
Iron	-0.54	-0.18	**-0.42**	**0.98**
Magnesium	**0.77**	0.36	**0.83**	-0.51
Manganese	-0.7	-0.37	-0.62	**0.96**
Sulfur	0.41	-0.6	**0.91**	-0.57
Zinc	-0.8	-0.29	-0.65	0.47

4.2.3 Vegetative attributes response foliar fertilizer treatment, 2023

- Soil Plant Analysis Development (SPAD)

The water regime exerted a significant effect on SPAD values ($p<0.001$). Overall, the irrigated plants had significantly higher SPAD values than the non-irrigated ones. SPAD values ranged from 42.67 to 59.96 in irrigated plants and from 38.69 to 61.36

in non-irrigated plants. The phenological stage effect was also significant ($p<0.001$), with the highest values obtained at R1 (mean ≈ 56.9), followed by R4, and the lowest at R6 and V12 (Figure 64). Mv 352 had significantly higher SPAD values than Fornad ($p<0.001$), which was likely due to more retention of chlorophyll. The Hybrid*Water, Hybrid*Stage, and Hybrid*Stage*Water interactions were significant, indicating SPAD values were more stable under non-irrigated conditions in Mv 352. The foliar fertilizer treatment had no significant effect but had minor interactions. The largest positive response to foliar fertiliser was observed in the Fornad hybrid, which increased its SPAD values by 10.22% at R1, 10.27% at R4 and 4.21% at R6 under non-irrigated conditions. This reflects the high physiological tolerance and stability of the Fornad hybrid to drought stress. The continuous and high-level increase in SPAD readings during critical reproductive phases reflects its ability to maintain chlorophyll content and photosynthetic efficiency whenever water availability is not favorable. This type of response towards foliar fertilization reveals the potential of Fornad as a drought-resistant hybrid to culture in areas where water is scarce. Comparable findings have been reported in previous studies where foliar spray of micronutrients such as silicon and zinc, and zinc and trehalose, significantly increased chlorophyll content and plant performance under drought in maize (Lamlom et al., 2024; Klofac et al., 2023). Similarly, Kathirvelan et al. (2025) reported that under drought stress, foliar application of nano-ZnO (100 ppm) and nano-MnO (20 ppm) significantly increased the levels of both chlorophyll a and b.

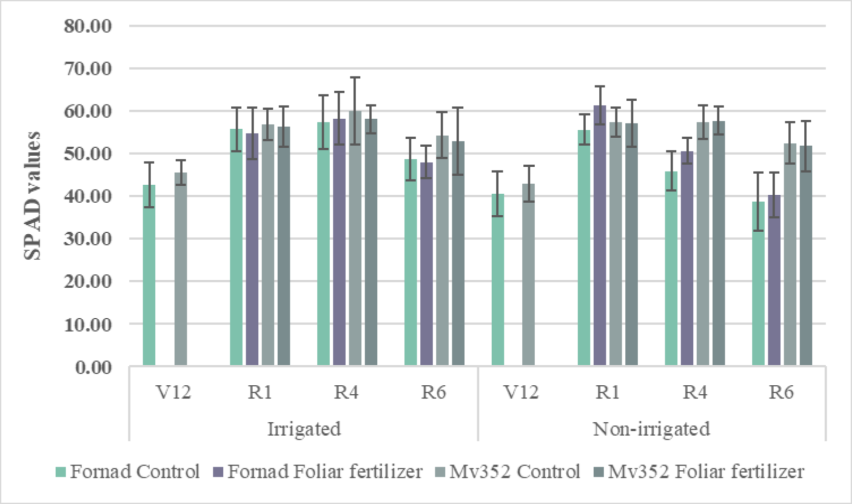

Figure 64. SPAD values of maize response to foliar fertilizers at different phenological stages under irrigated and non-irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.001$ | Treatment: ns | Water regime: $p<0.001$ | Interactions: Hybrid*Treatment, Hybrid*Water regime and Treatment*Water regime: $p<0.05$, Hybrid*Phenological Stage, Phenological Stage*Water regime and Hybrid*Phenological Stage*Water regime: $p<0.001$. (Debrecen, 2023).

- Normalised difference vegetation index (NDVI)

The hybrid effect was highly statistically significant ($p<0.001$), with Mv 352 possessing the highest NDVI values. Phenological stage also demonstrated a statistically strong influence, with peaks of NDVI at R1 and V12. Hybrid*Phenological Stage*Water Regime, Phenological Stage*Water Regime, and Hybrid*Phenological Stage interactions were significant, confirming that the NDVI values vary over development stages under different irrigation conditions (Figure 65). In contrast to the effects of the water regime on SPAD, NDVI remained unaffected. This is inconsistent with the findings of Tamás et al. (2023). They reported that, during the drought period, irrigation had a significant positive effect on the NDVI. NDVI values ranged from 0.54 to 0.85 in irrigated plants and from 0.51 to 0.51 in non-irrigated plants. Furthermore, despite the non-significant effect of foliar fertilizers treatment on NDVI, it had only a subtle influence, as it increased the NDVI values of the Fornad hybrid by 2.5% at R1 under irrigated conditions and 1.9% and 6.5%, at R1, R6, respectively, under non-irrigated conditions. whereas Mv 352 had one single positive response to treatment in R4 under irrigated conditions, with an increase of 1% in NDVI values.

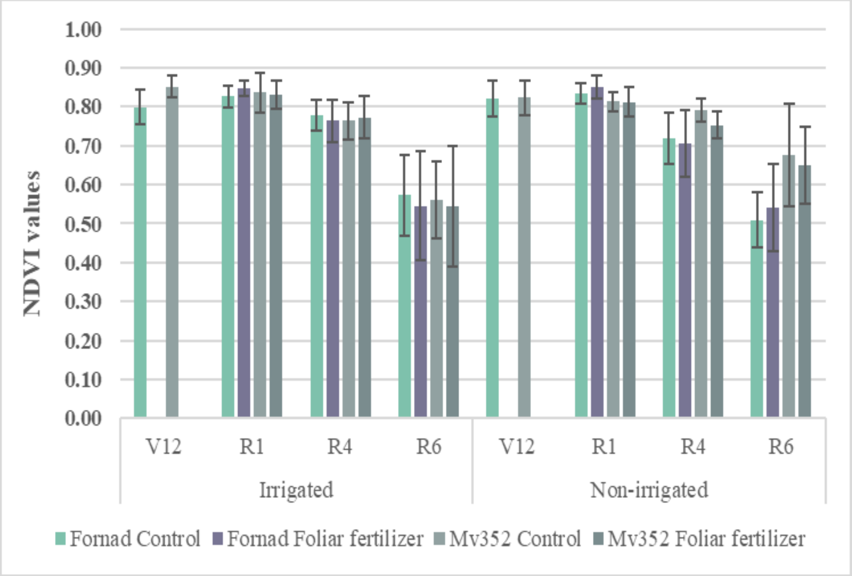

Figure 65. NDVI values of maize response to foliar fertilizers at different phenological stages under irrigated and non-irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Treatment: ns | Water regime: ns | Interactions: Hybrid*Phenological Stage and Phenological Stage*Water regime: $p<0.05$, Hybrid*Phenological Stage*Water regime: $p<0.001$. (Debrecen, 2023).

- Leaf area index (LAI)

Water regime had a significant impact on LAI ($p=0.001$), with irrigated plants having higher LAI. Overall, LAI values ranged from 2.53 to 6.76 in irrigated plants and from

2.73 to 6.37 in non-irrigated plants. Consistently, LAI has been found to decrease with the severity of water stress (Karam et al., 2003; Nawaz et al., 2024). Phenological stage effect was the most significant, whereby the R1 and R4 stages had the highest LAI values and V12 had the lowest. In addition, the hybrid effect was also significant (p<0.01), with Mv 352 significantly maintaining higher LAI compared to Fornad. However, the effect of treatment was not significant, yet we can observe greater negative responses of hybrids to the applied nutrition, with reductions of 14.3% and 9.5% in the LAI values for Fornad, in R6 under irrigated conditions and in R4 under non-irrigated conditions, respectively (Figure 66). However, a 19.1% reduction in LAI values was observed in Mv 352 at R4 under non-irrigated conditions. Lamlom et al. (2024) reported that combined Si + Zn foliar treatments under drought conditions resulted in higher leaf area than the controls, which supports the significant impact of irrigation on LAI and the subtle, yet cultivar-dependent, response to foliar nutrition.

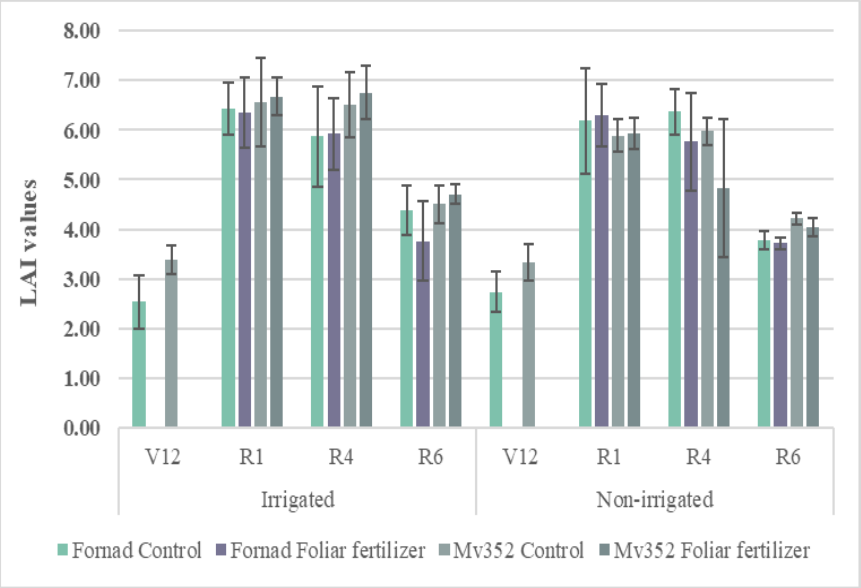

Figure 66. LAI values of maize response to foliar fertilizers at different phenological stages under irrigated and non-irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Treatment: ns | Water regime: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.05, Hybrid*Water regime: p<0.01. (Debrecen, 2023).

- Stem diameter

There was no significant effect observed regarding stem diamater. However, it was proven that plant stem diameter increases significantly with increasing irrigation water (Rasool et al., 2020). However, foliar fertilization influenced both hybrids differently in irrigated conditions (Figure 67). It increased the Mv 352 stem diameter by 5.6% and reduced the Fornad stem diameter by 7.6%. In contrast to our results, Ali et al. (2024) reported that the use of SNPs (silicon nanoparticles) significantly enhanced maize morphological aspects, including stem diameter, with no significant differences between irrigation regimes. Based on their results, the combination of SNPs and micro silica was found to significantly increase stem width. They subsequently advocated the use of foliar application of SNPs, particularly in circumstances where the plant was exhibiting symptoms of stress, such as drought.

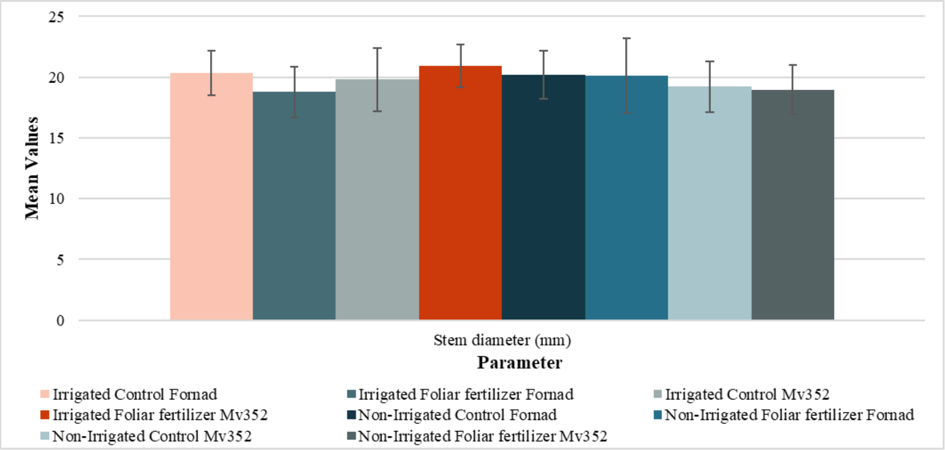

Figure 67. Maize stem diameter. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2023).

4.2.4 Grain quality traits response to foliar fertilizer treatment, 2023

Moisture content was more influenced by the genetic variation as well as by foliar fertilizer ($p<0.001$). Surprisingly, high moisture content was attributed to the control plot rather than to the one treated with foliar fertilizer, suggesting accelerated kernel maturation (Figure 68). Among the hybrids, Mv 352 had higher moisture content by 2.3% than Fornad. The effect of water regime regarding moisture content wasn't significant, yet according to our findings, drip irrigation slightly decreased grain moisture content for both hybrids. In contrast, there was no significant differences that could be observed in terms of grain oil content. This stability implies that oil content could be influenced to some extent under genetics and not at all by irrigation nor foliar treatment. However, we could notice that foliar fertilization improved only the oil content of Mv 352 by 0.5% under irrigated conditions and by 4.5% under non-irrigated conditions. Irrigation also enhanced only the oil content of Mv 352 by 5.7%. Protein content, on the other hand, was highly affected by Hybrid ($p<0.001$) where Mv 352 had higher protein content. Treatment and water regime had no influence whatsoever, showing again genetic control. Yet, the treatment has improved the protein content of Fornad hybrid by 10% under irrigation and Mv hybrid by 8% under non-irrigated conditions. Meanwhile, the drip irrigation enhanced Mv 352 protein content by 4.8%. It was proved by Farooqi et al. (2012) that a reduction in maize grain protein contents was caused by water stress at the reproductive stage in maize. They found that applying potassium foliar fertilizer under no stress significantly increased protein content, while the minimum value was observed when no potassium was applied to the soil under water stress. Starch content, also, was significantly influenced by hybrid type ($p<0.001$), where it was higher in Fornad. No effect from water regime or foliar treatment was significant.

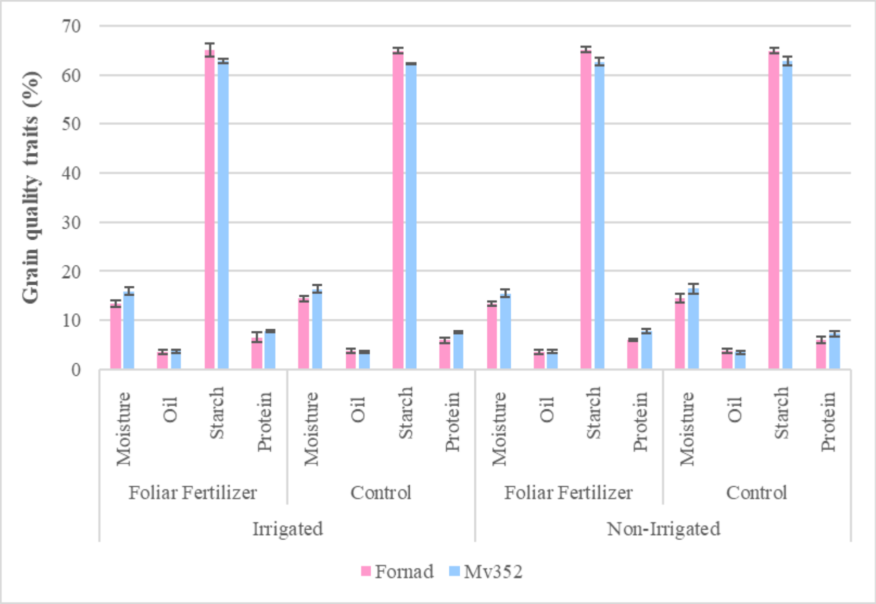

Figure 68. Grain quality traits of maize. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2023).

4.2.5 Grain yield attributes response to foliar fertilizer treatment, 2023

- Thousand grain weight, number of grains per cob, cob and grain weights

The thousand-grain weight was heavily influenced by hybrid ($p<0.001$), water regime ($p<0.01$) and their interaction Water Regime*Hybrid as well as Treatment*Hybrid ($p<0.01$). Among the hybrids, Mv 352 had the highest thousand-grain weight (Figure 69). As statistically proven, the non-irrigated plot resulted in a greater thousand-grain weight, which is possibly a compensatory mechanism in fewer but heavier grains. This was particularly evident in Mv 352, which contributed to an 18.7% higher thousand-grain weight in the non-irrigated, than in the irrigated plot. This contradicts what Rasool et al. (2020) found, that 1000-grain weight values increased significantly with decreasing irrigation water deficits. Foliar fertilizer treatment enhanced the thousand-grain weight of the Fornad hybrid by 13.3%, even though it was not significant. The water regime significantly affected the number of grains per cob

($p<0.001$). For instance, under irrigated conditions, the number of grains per cob was observed to be greater than that produced under non-irrigated conditions by an average of 65 grains per cob. The significance of the treatment effect ($p<0.01$) and the hybrid effect ($p<0.001$) were both statistically verified. The Water regime*Hybrid*Treatment, as well as the Water regime*Hybrid and Treatment*Hybrid interactions, were significant. Under irrigated conditions, the application of foliar fertilizers resulted in an increase of the number of grains per cob produced by Mv 352 by 44.8%, while Fornad negatively responded to the treatment with a 18% reduction in its number of grains per cob. However, under non-irrigated conditions, the efficiency of the treatment implemented was achieved in the performance of Fornad, represented by the increase in 18% in the number of grains per cob, compared to the increase of 7.9% achieved by Mv 352. Potarzycki and Grzebisz’s study (2009), found that zinc foliar fertilizer rates significantly influenced the total number of kernels per cob, with maize plants given 1.0 kg Zn ha^{-1} producing 17.8% more kernels per cob than those given NPK only (control). The thousand-grain weight was also significantly positively affected by zinc rates in this study. The cob weight was significantly affected by the hybrid type ($p<0.001$) and Treatment*Hybrid interaction ($p<0.01$). Overall, Mv 352 had heavier cobs compared to Fornad. The treatment has enhanced the cob weight of Fornad hybrid in particular under both irrigated and non-irrigated conditions, with 24% and 44%, respectively, indicating optimal use of nutrients. In contrast, the performance of Mv 352 was negative. The variation in the performance of hybrids can be attributed to their genetic variations and their ability and behavior when interacting with various factors. Grain weight was significantly affected by the water regime ($p<0.05$) and Water regime*Treatment*Hybrid interaction ($p<0.01$). Overall, the irrigated plants produced heavier grains compared to the ones grown under non-irrigated conditions. Fornad inherently produced heavier grains compared to Mv 352, reflecting its greater grain-filling capacity. Meanwhile, interestingly, we can see that Fornad grain’s weight was sensitive to foliar treatment, as it reacted vigorously under both water regimes. Foliar application reduced its grain weight by 10.6% under irrigated conditions, whereas under non-irrigated conditions it enhanced it by 33.6%. This differential response could mean that during drought stress, foliar fertilization plays a compensatory role towards increasing assimilate allocation and grain filling in Fornad, whereas under irrigated conditions, treatment might have disrupted optimal source-sink dynamics or triggered excessive uptake of nutrients without leading to gain yield benefit.

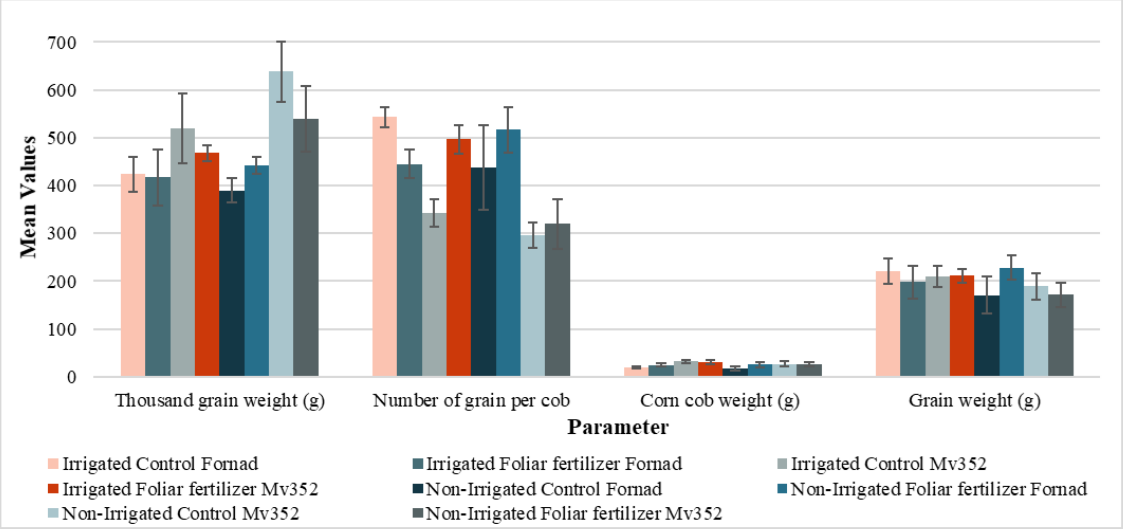

Figure 69. Maize grain attributes. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2023).

- Ear length, ear height, ear weight, and ear diameter

Ear length was significantly influenced by water regime ($p<0.001$), treatment ($p<0.05$) and hybrid ($p<0.01$). The Treatment*Hybrid interaction was also significant. Therefore, irrigated plants had the longest ears, indicating treatment synergy with genetic potential. These findings are consistent with those of Rasool et al. (2020), who reported that ear length values increased significantly with decreasing levels of irrigation water. Foliar application enhanced also the length of ears, in particular in Fornad hybrid under both water regimes. The height of the maize ear was significantly affected by water regime, hybrid, treatment, and their interactions ($p<0.001$), except for Water regime*Treatment. Mv 352 had a taller ear position than Fornad. However, foliar feeding decreased the ear height of both hybrids under both water regimes, with the exeption of Mv352 under non irrigated condition where its ear height improved by 5.3%, and that could be explained possibly due to more efficient plant type resulting from the higher level of nutrient assimilation (Figure 70). Ear weight was significantly affected by water regime and Water Regime*Treatment*Hybrid interaction ($p<0.05$). Thus, irrigated plants had heavier ears than those grown in non-irrigated conditions. In addition, Rasool et al. (2020) found that irrigation treatments significantly impacted ear weight, with ear weight values showing a marked increase in conjunction with reduced irrigation water deficits. However, in contrast to our results, another study showed that the quantity of irrigation did not significantly affect yield components. However, medium irrigation produced ears that were 30.8% and 4.2% heavier than those produced by treatments with lower and higher irrigation quantities, respectively (Gu et al., 2021). Despite non-significantness among the hybrids, Fornad produced heavier ears. Similarly, there was an effect of the foliar treatment on the performance of the hybrids, this could be explained by their interaction with the treatment and the environmental conditions. Thus, a 34.6% improvement in ear weight was achieved in Fornad due to the foliar application in non-irrigated environment. Regarding ear diameter, water regime ($p<0.01$), hybrid ($p<0.001$) and Water Regime*Treatment*Hybrid ($p<0.001$) interaction effects were significant. Overall, irrigated plants had higher ear diameter. Also, Mv 352 had greater ear diameter comparing to that of Fornad hybrid. On the other hand, foliar treatment strongly increased the ear diameter of Fornad by 7% in non irrigated conditions. This response may indicate a generalized physiological response, perhaps linked with enhanced photosynthate availability and nutrient transport to the ear.

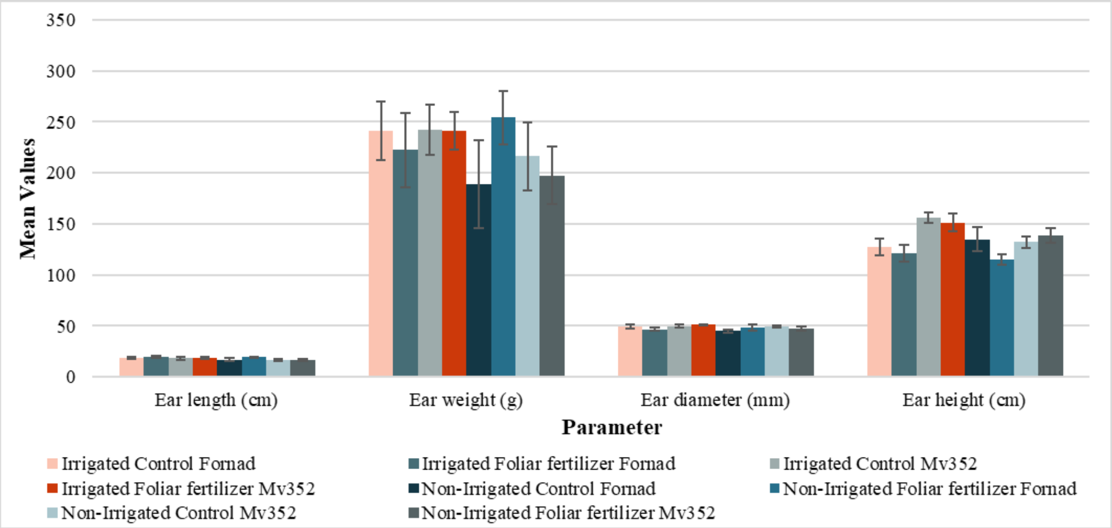

Figure 70. Maize ear characteristics. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2023).

4.2.6 Grain yield in 2023

The water regime significantly affected yield ($p<0.001$), with irrigated plants yielding more (mean=13.59 t ha^{-1}) than non-irrigated (mean=12.48 t ha^{-1}). Thus, maize yield under irrigated conditions was 8.8% higher than under non-irrigated conditions, highlighting environmental sensitivity (Figure 71). Studies have demonstrated the importance of irrigation in improving water availability for maize crops, which is crucial for optimizing maize production in regions experiencing water stress or irregular rainfall (Nagy, 2003). Furthermore, combining irrigation with appropriate fertilization practices significantly enhances maize yield and quality, highlighting the synergistic effect of these agronomic factors in maize cultivation (Pepó, 2018; Bramdeo and Rátonyi, 2020). Elevated irrigation levels were also found to increase maize yield and harvest index, though this was accompanied by a precipitous decline in yield with increasing water deficit (Farré and Faci, 2006). Likewise, Farooqi et al. (2012) found that the maximum yield in their study was obtained in plots (S0K1F2) with no stress, with soil-applied potassium and 1% K_2O sprayed onto the foliage. While, the minimum economical yield was obtained in plots (S1K0F0) under water stress with no soil-applied potassium and no foliar potassium spray. To that end, the water stress experienced during the reproductive stage led to a substantial diminution in the yield of maize. Fornad hybrid outperformed Mv 352 by producing a higher yield of 13.46 t ha^{-1} compared to 12.60 t ha^{-1} (Figure 72). However, without foliar fertilization, Mv 352 had a better performance compared to Fornad. There was also a treatment effect, and it was statistically significant. In accordance, due to foliar fertilization, the yield was enhanced by 14% in comparison with the control. Therefore, foliar fertilizer nutrition improved yield over the irrigation conditions and for both hybrid, which was statistically confirmed through the significant Treatment*Hybrid and Water regime*Treatment interactions. Tejada et al. (2018), also found that the use of biostimulant foliar fertilizers improved the yield by 14.6%. In fact, Fornad under foliar fertilization tended to yield more than Mv 352, even under non-irrigation, reflecting high responsiveness and resilience. For instance, under non-irrigated conditions, using foliar nutrition, Fornad yield surpassed the control by 4.2 t ha^{-1}, while that increase under irrigation conditions was 2.2 t ha^{-1}. In their study, Ali et al. (2024) found that the use of SNPs (silicon nanoparticles) significantly enhanced maize grain yield. SNPs were found to produce a higher yield than the other treatments, especially when 100% of the irrigation water was used.

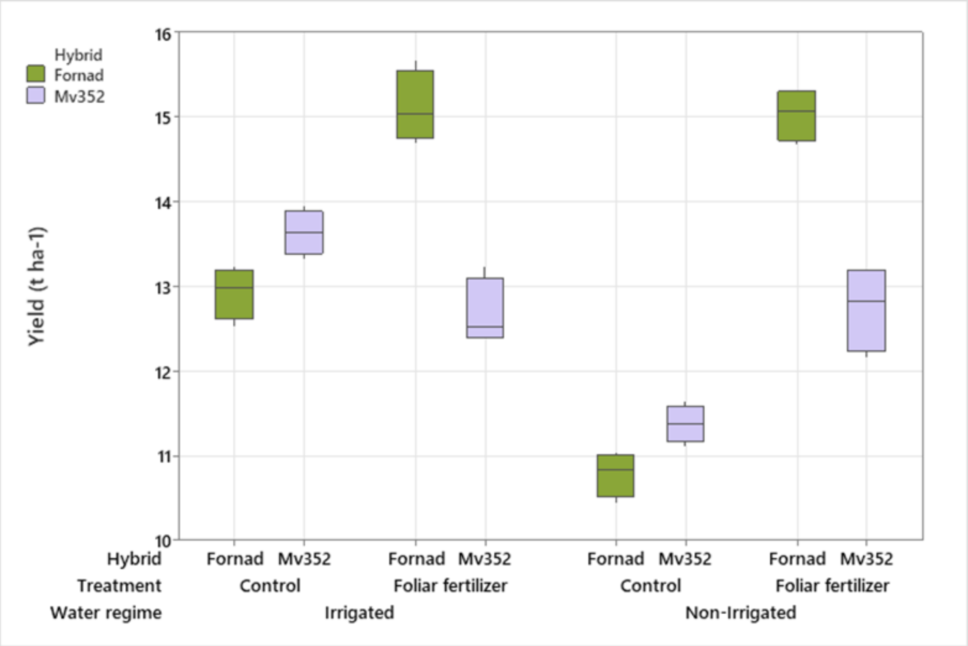

Figure 71. Maize yield response to foliar fertilization under irrigated and non irrigated conditions. Water regime effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Interactions: Water regime*Treatment and Treatment*Hybrid: p<0.001. (Debrecen, 2023).

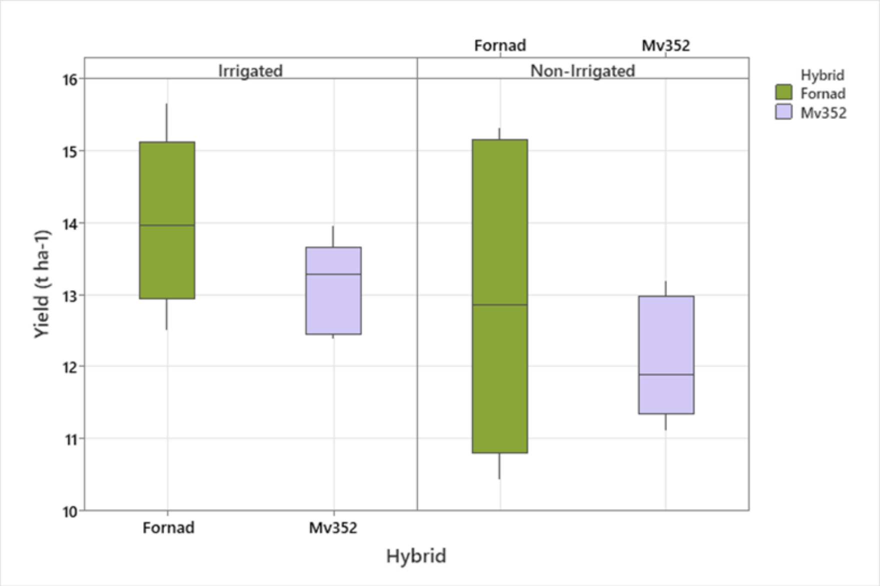

Figure 72. Maize yield under irrigated and non irrigated conditions. Water regime effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Interactions: Water regime*Treatment and Treatment*Hybrid: p<0.001. (Debrecen, 2023).

4.2.7 Correlation analysis between grain quality traits and yield, 2023

Under irrigated conditions, the correlation analysis revealed a moderate positive correlation between Fornad's yield and protein content, suggesting that foliar treatments or favourable climatic conditions enhanced both (Table 7). There was also a slight positive correlation between Fornad's yield and starch content. Meanwhile, moisture and oil contents showed a strong negative correlation with the hybrid's yield. By contrast, Mv 352's yield showed a strong positive correlation with moisture content and negative correlations with oil, protein, and starch contents. In contrast, under non-irrigated conditions, the correlation analysis showed that Fornad's yield was strongly negatively correlated with moisture, moderately negatively correlated with protein, and slightly negatively correlated with oil (Table 7). Meanwhile, there was a weak positive trend with starch content. In contrast, Mv 352's yield demonstrated moderate positive correlations with protein and oil contents, as well as slight negative correlations with moisture and starch contents.

Table 7. Correlations between maize yield and grain quality traits under irrigated and non-irrigated conditions. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p<0.05$. (Debrecen, 2023).

	Moisture	**Oil**	**Protein**	**Starch**
Fornad irrigated	-0.83	-0.83	0.48	0.15
Fornad non-irrigated	-0.64	-0.39	-0.01	0.11
Mv 352 irrigated	0.60	-0.51	-0.24	-0.55
Mv 352 non-irrigated	-0.11	0.34	0.34	-0.13

4.3 Comparative analysis of the results of the study years 2022 and 2023 under irrigated conditions

4.3.1 Dry matter and nutrient accumulation in two years 2022 and 2023 under irrigated conditions

Dry matter content was highly influenced by three main factors: year ($p<0.01$), phenological stage ($p<0.001$), and plant part ($p<0.001$), indicating intense developmental and physiological patterns in biomass development. The non-significant impact of hybrid indicates limited genotypic variation for total biomass under irrigated conditions (Figure 73, Figure 74). However, Fornad performance over the two study period was significantly different. The interactions (Year*Phenological Stage, Year*Plant Part, and Year*Hybrid*Phenological Stage) that represent the modulation of biomass allocation by the environment over the years and between the parts of the plant, were not significant. The accumulation of dry matter, based on Tukey test, progressed steadily with the growth of the plants until a slight decrease at R4. However, this decrease did not differ statistically from the accumulation in the previous stage (R1). Dry matter accumulation per phase was: V12 (10.0 g plant^{-1}), R1 (50.6 g plant^{-1}), R4 (47.4 g plant^{-1}) and R6 (61.5 g plant^{-1}). This highlights the importance of the reproductive stages in dry matter accumulation. Kernels accumulated the most in dry matter (120.5 g plant^{-1}), followed by stalk+tassel and leaves, while cob and husks accumulated the lowest. 2022 accumulated significantly more dry matter when compared with 2023 (46.87 g plant^{-1} versus 37.90 g plant^{-1}), likely reflecting seasonal climatic variation or soil water availability despite irrigation (Figure 75).

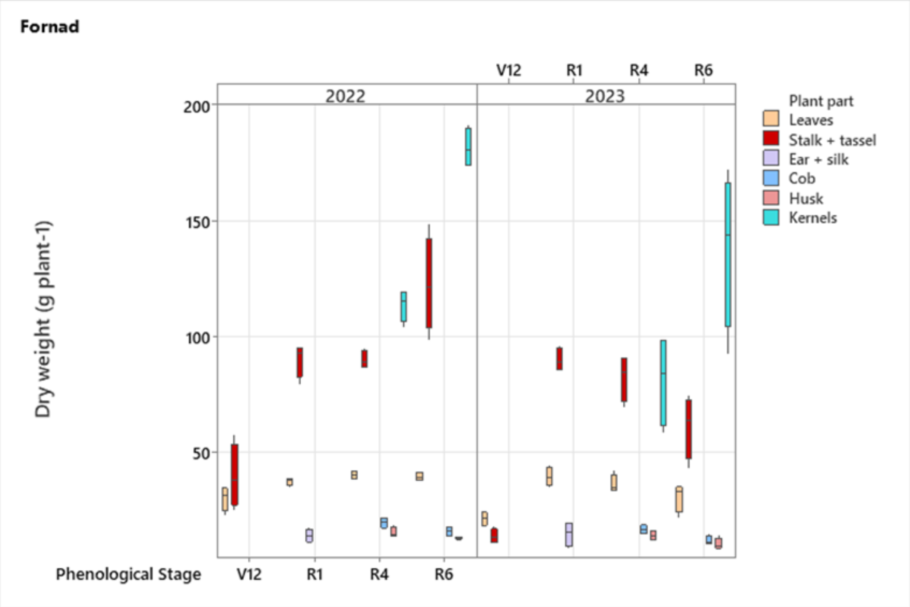

Figure 73. Dry weight accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.01 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

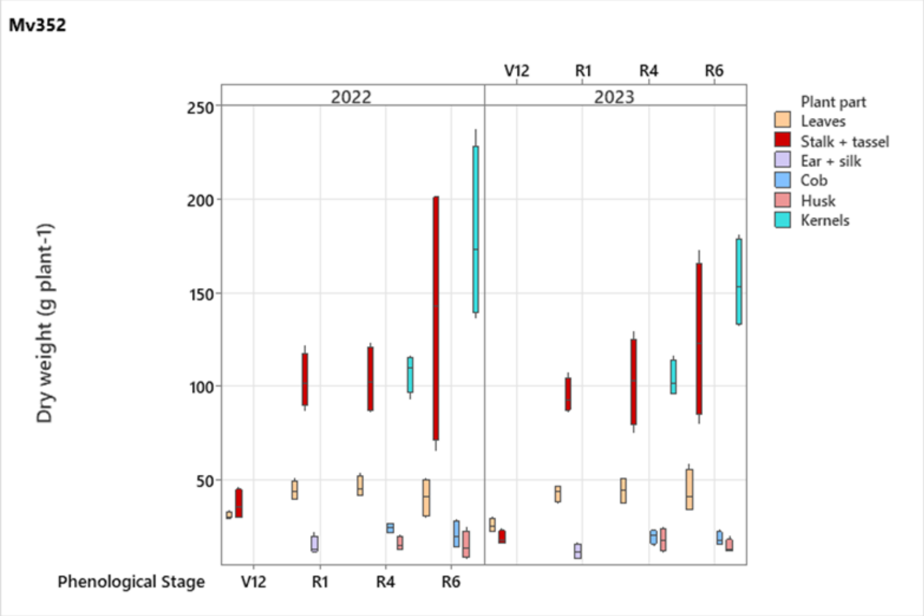

Figure 74. Dry weight accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.01 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

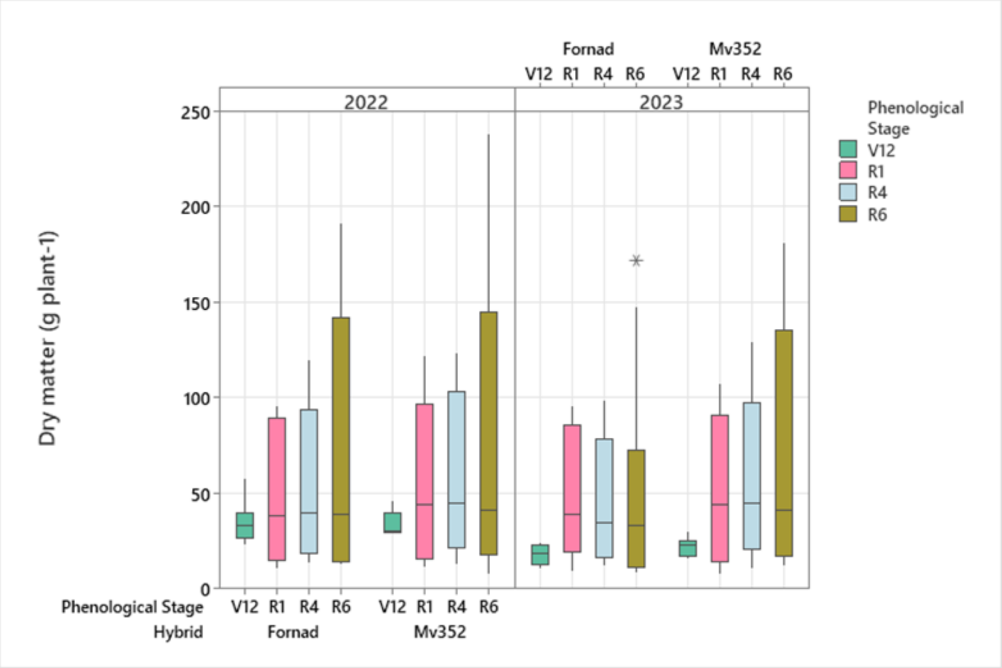

Figure 75. Dry weight accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.01 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

Nitrogen concentration was highly affected by year, phenological stage, hybrid, and plant part (p<0.001). Additionally, four effects were significant (p<0.001), including Year*Phenological stage, Hybrid*Plant Part, and Year*Hybrid*Stage, showing that patterns of nitrogen remobilization were complicated and affected by both environment and genotype. As the crop grow, the nitrogen accumulation declined, from V12 to R6, following the process of remobilization of nutrients from vegetative to reproductive organs. Mv 352 had accumulated more nitrogen compared to Fornad, which means that the two genotypes also vary in nutrient uptake efficiency (Figure 76, Figure 77). Leaves had the highest content of nitrogen, validating their role as the primary metabolic organ. Kernels and cob accumulated the lowest nitrogen during the later stages, indicating high remobilization and partitioning towards grain development. When comparing the accumulation of nitrogen between the two cropping seasons, 2023 accumulated significantly more nitrogen than in 2022 (Figure 78).

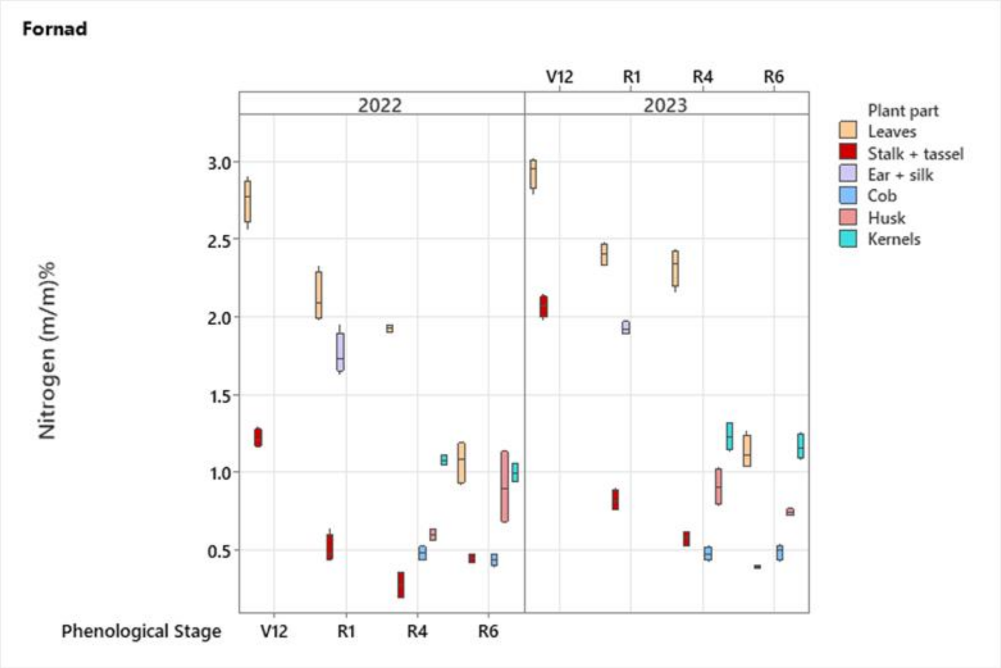

Figure 76. Nitrogen accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Hybrid and Year*Hybrid*Phenological Stage: p<0.05, Hybrid*Plant Part: p<0.001. (Debrecen, 2022-2023).

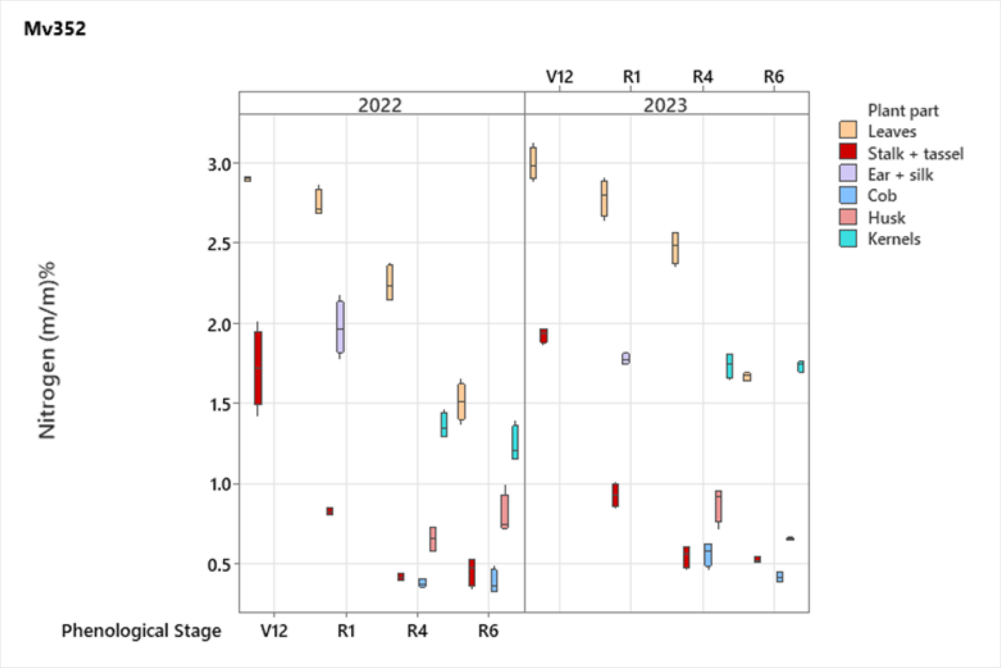

Figure 77. Nitrogen accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Hybrid and Year*Hybrid*Phenological Stage: p<0.05, Hybrid*Plant Part: p<0.001. (Debrecen, 2022-2023).

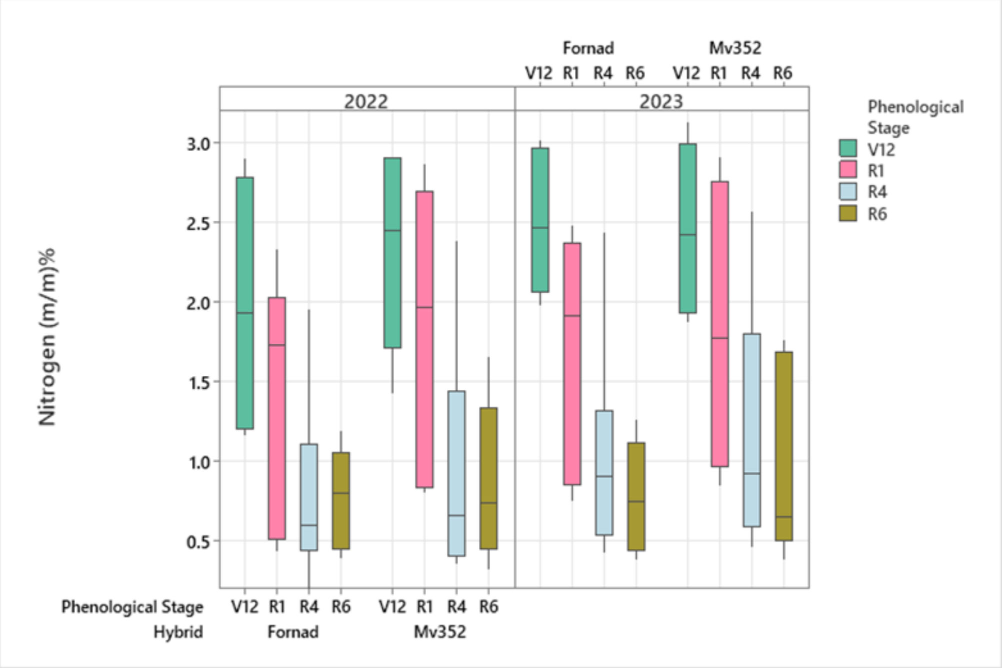

Figure 78. Nitrogen accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.001$ | Year: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Year*Phenological Stage, Year*Hybrid and Year*Hybrid*Phenological Stage: $p<0.05$, Hybrid*Plant Part: $p<0.001$. (Debrecen, 2022-2023).

Phosphorus uptake was significantly affected by phenological stage and plant part ($p<0.001$), while year and hybrid as main effects were non-significant. Yet, P accumulation peaked in 2022, especially in Fornad (Figure 81). Nevertheless, some interactions were significant, including Year*Phenological Stage, Year*Plant Part, Hybrid*Phenological stage, Hybrid*Plant Part, and Year*Hybrid*Phenological stage. These results indicate that phosphorus partitioning was strongly governed by growth timing and organ type, with some influence from genotype and environment. As per the Tukey test, the highest concentration of phosphorus was found at V12 (4990 mg kg^{-1}) with gradual decline towards R6 (1856 mg kg^{-1}), indicating early uptake and distribution with plant growth. Kernels had the highest concentration (4279 mg/kg), showing the great demand for phosphorus during grain filling, while the lowest concentration was observed in the cob (1800 mg kg^{-1}) (Figure 79, Figure 80).

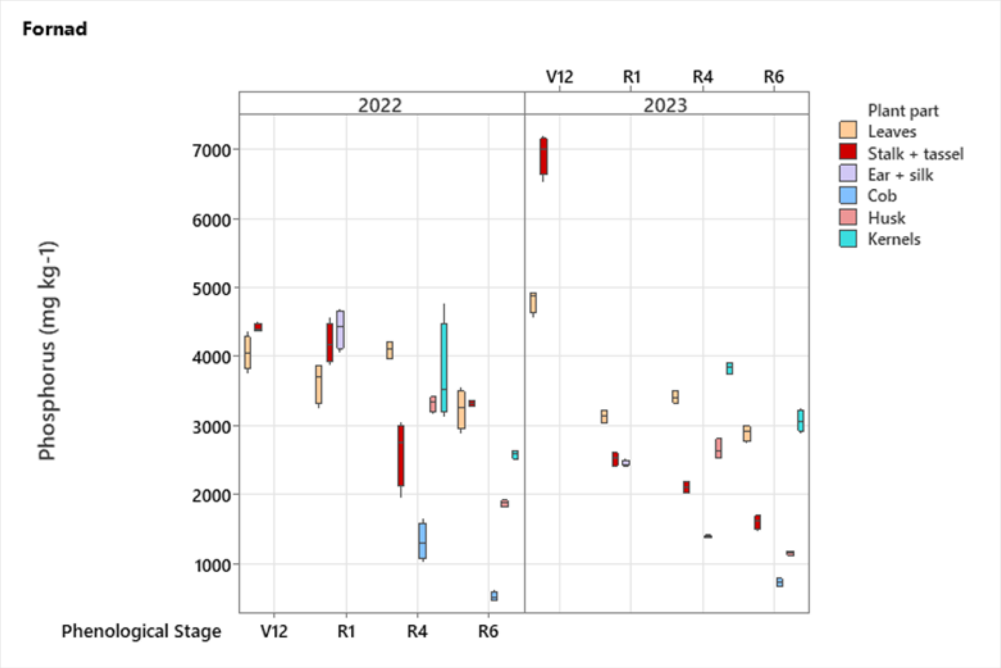

Figure 79. Phosphorus accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Hybrid*Plant Part and Hybrid*Phenological Stage: p<0.001, Year*Plant Part: p<0.01, Year*Hybrid*Phenological Stage: p<0.05. (Debrecen, 2022-2023).

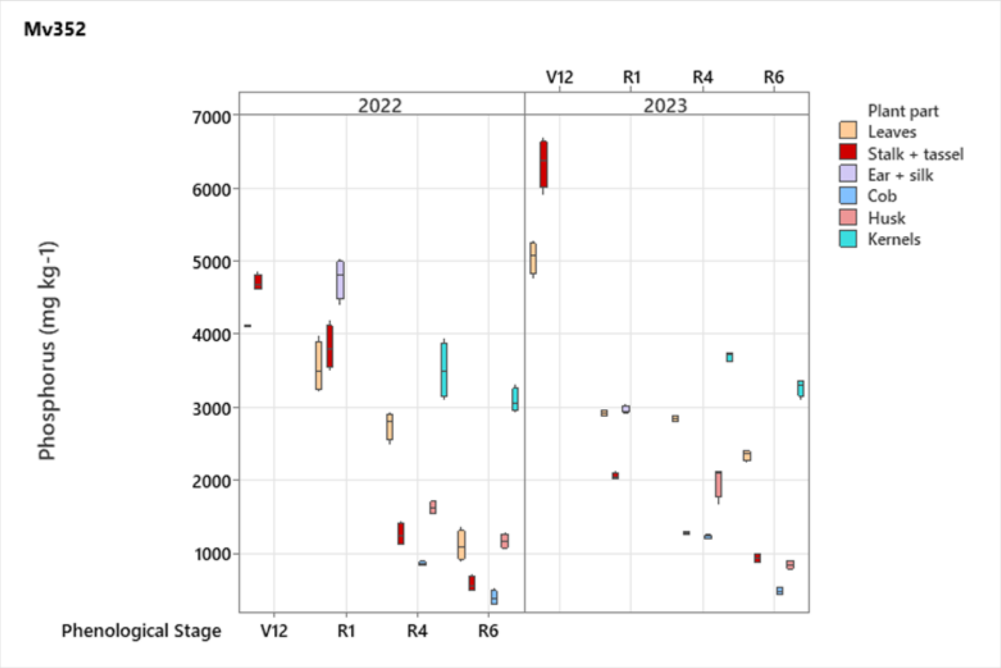

Figure 80. Phosphorus accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Hybrid*Plant Part and Hybrid*Phenological Stage: p<0.001, Year*Plant Part: p<0.01, Year*Hybrid*Phenological Stage: p<0.05. (Debrecen, 2022-2023).

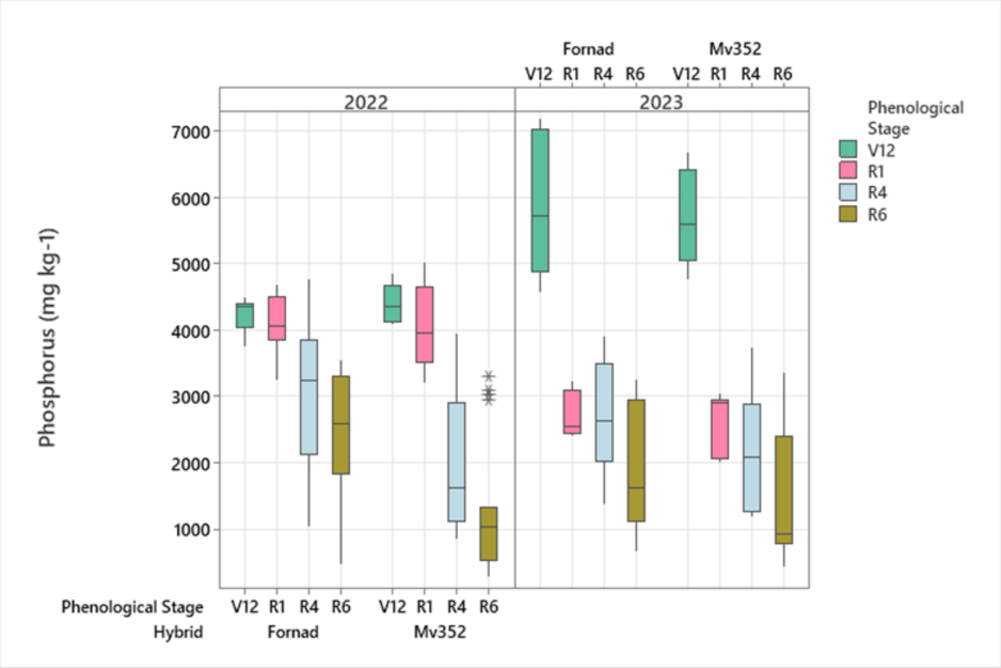

Figure 81. Phosphorus accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Year: ns | Plant Part: $p<0.001$ | Interactions: Year*Phenological Stage, Hybrid*Plant Part and Hybrid*Phenological Stage: $p<0.001$, Year*Plant Part: $p<0.01$, Year*Hybrid*Phenological Stage: $p<0.05$. (Debrecen, 2022-2023).

Potassium content was strongly influenced by year, phenological stage, and plant part ($p<0.001$), with no interactions. Absence of significant interactions indicates relatively stability in the behavior of potassium uptake across genotypes. However, K highest uptake and accumulation was observed in Mv 352. The Tukey test indicated that potassium accumulation was significantly higher in 2023 (22809 mg kg^{-1}) than in 2022 (19265 mg kg^{-1}), perhaps due to environmental or soil differences (Figure 84). The peak was reached at V12 (41222 mg kg^{-1}) with a sharp drop by R6 (10855 mg kg^{-1}), which point out the greater needed of potassium especially in the early stage of plant development and in the vegetative parts in particular than in the reproductive parts of the plant. K demand by the stalk+tassel was of major significance as it held the most potassium content, while kernels held the least, which is in line with potassium mobility and activity in vegetative tissues (Figure 82, Figure 83).

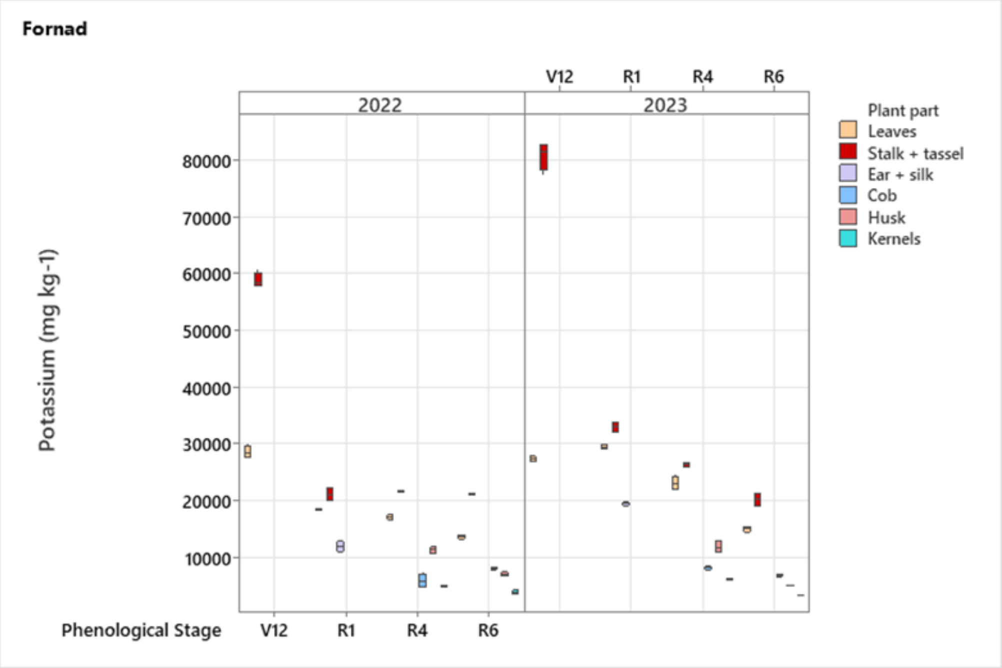

Figure 82. Potassium accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

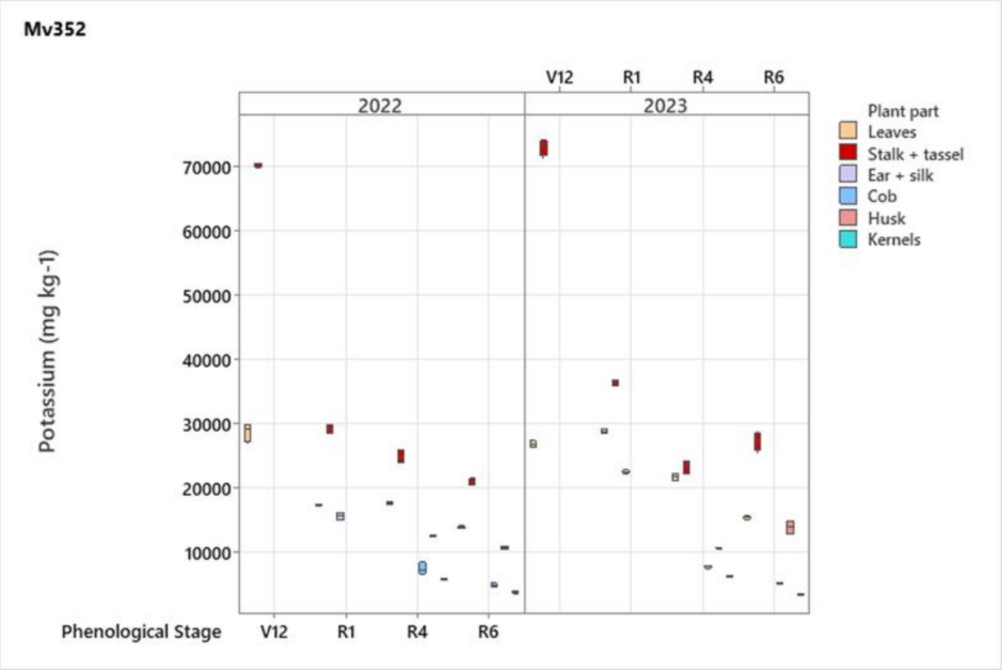

Figure 83. Potassium accumulation within Mv 352 hybrid as a function of pheno- logical stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

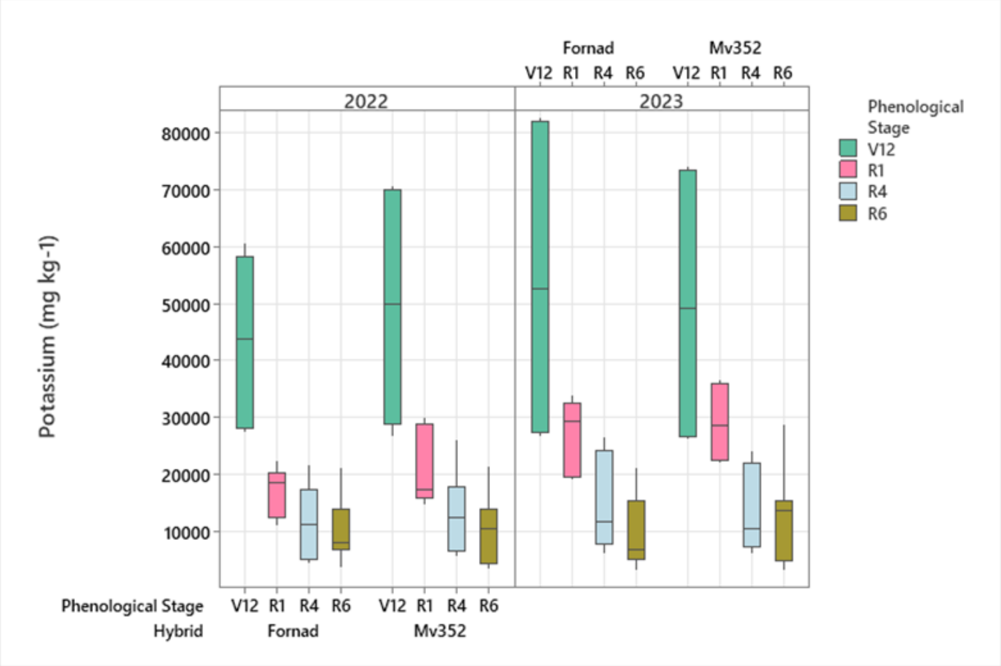

Figure 84. Potassium accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2022-2023).

Year, phenological stage, and plant part were all extremely significant ($p<0.001$). Hybrid ($p<0.05$) was also significant, as were the interactions Year*Hybrid and Year*Plant Part. The responsiveness of calcium to genotype differences and years was high reflecting the environmental dependence with regard to uptake (Figure 87). Thus, calcium accumulation was higher in 2023 than in 2022, and there was a more significant uptake in Fornad. Calcium accumulation by the leaves and stalk was largely compared to the ear and its components during the whole growing season, which supports the fact that calcium is not easily mobilized in the plant. The demand for Ca nutrient was relatively high at V12 and R1, which increased as the plant grew to reach its maximum at the maturity stage (Figure 85, Figure 86).

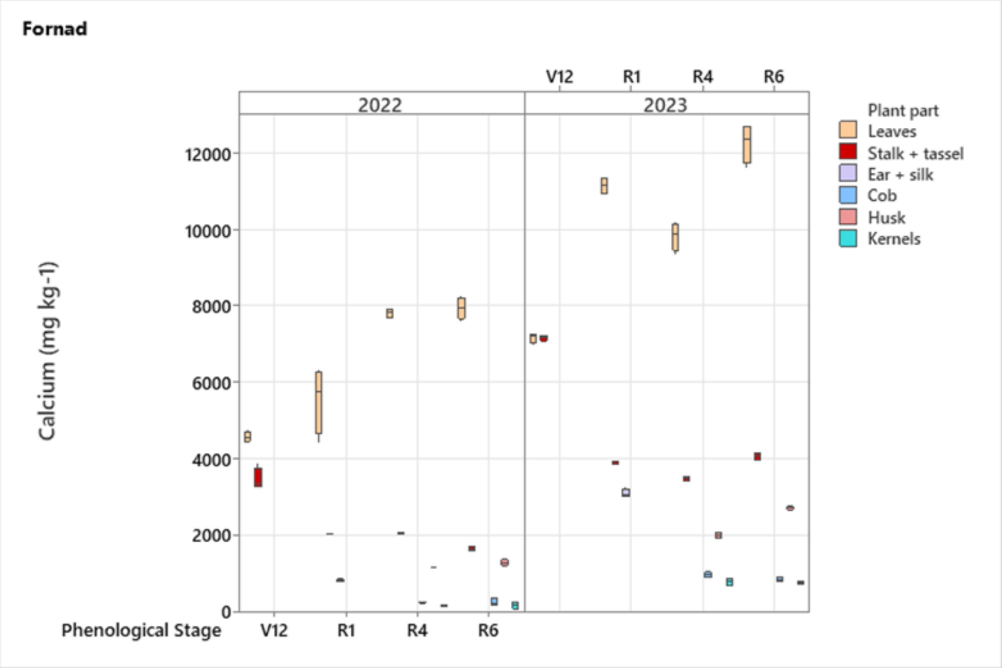

Figure 85. Calcium accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Hybrid: p<0.05, Year*Plant part: p<0.001. (Debrecen, 2022-2023).

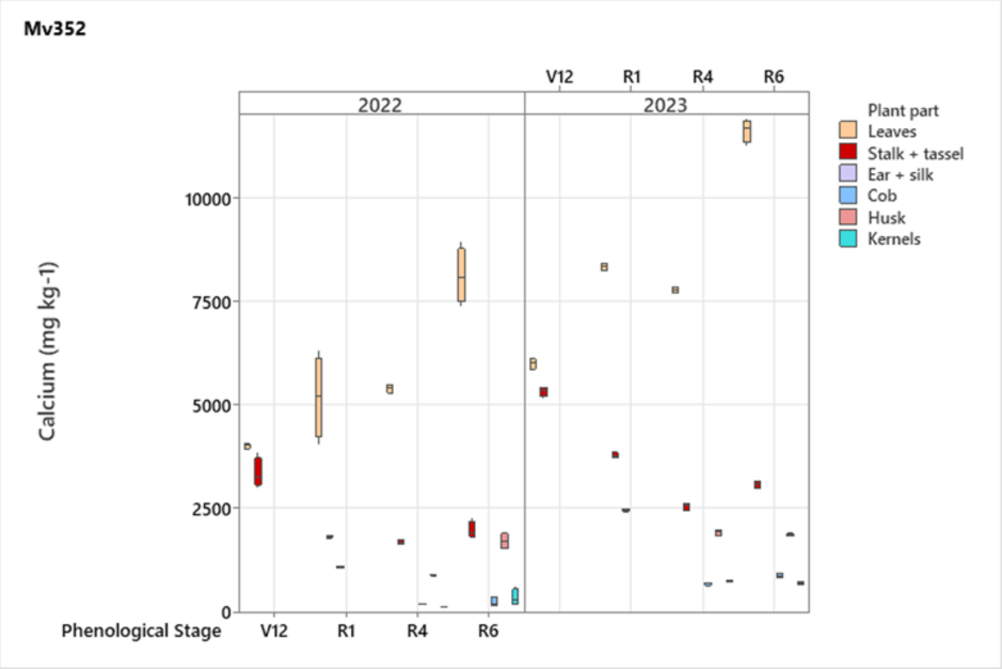

Figure 86. Calcium accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Hybrid: p<0.05, Year*Plant part: p<0.001. (Debrecen, 2022-2023).

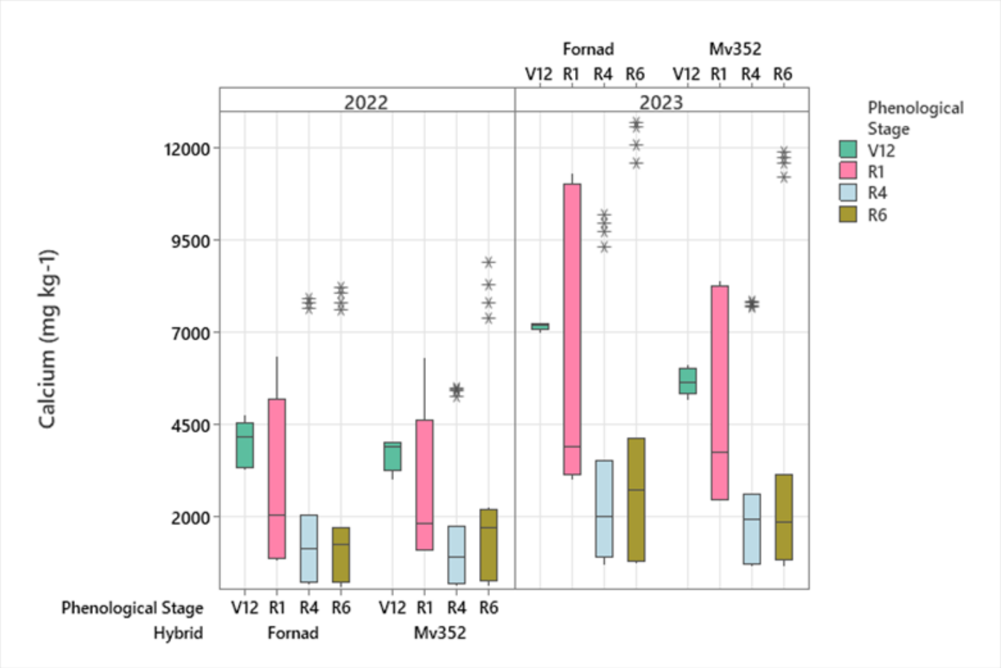

Figure 87. Calcium accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Year: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Year*Hybrid: $p<0.05$, Year*Plant part: $p<0.001$. (Debrecen, 2022-2023).

Year, phenological stage and plant part effects were significant for magnesium uptake ($p<0.001$), and so were the interactions: Year*Phenological Stage, Year*Hybrid, Year*Plant Part, Hybrid*Plant part, Year*Hybrid*Phenological Stage. They indicate that environmental and genetic factors determine patterns of maize magnesium distribution. Maize needed large magnesium content at early vegetative developmental stage in particular, this can be seen by the high nutrient uptake at V12 compared to later stages (Figure 88, Figure 89). Leaves had the highest content, followed by the stalk+tassel, as would be expected for a central metabolite in the formation and mobility of chlorophyll. Cob and husk had the lowest, as would be expected for moderately mobile nutrients. 2023 accumulated the highest magnesium content over the two study periods, as statistically proven (Figure 90). Despite the non significant difference, Fornad was found to have accumulated slightly higher magnesium content.

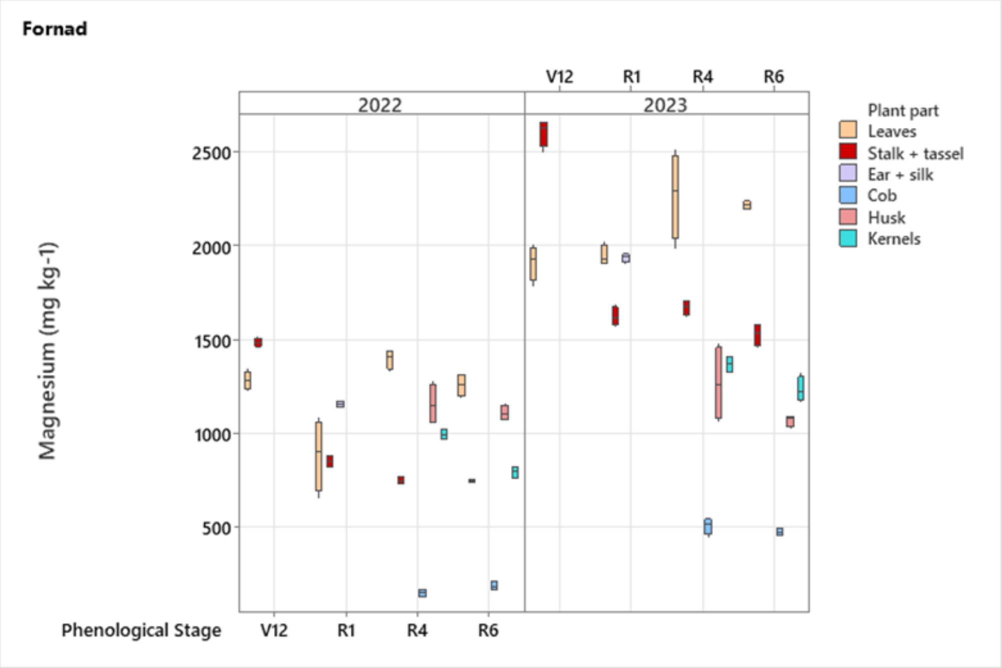

Figure 88. Magnesium accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage: p<0.01, Year*Hybrid, Hybrid*Plant Part and Year*Hybrid*Phenological Stage: p<0.05, Year*Plant Part: p<0.001. (Debrecen, 2022-2023).

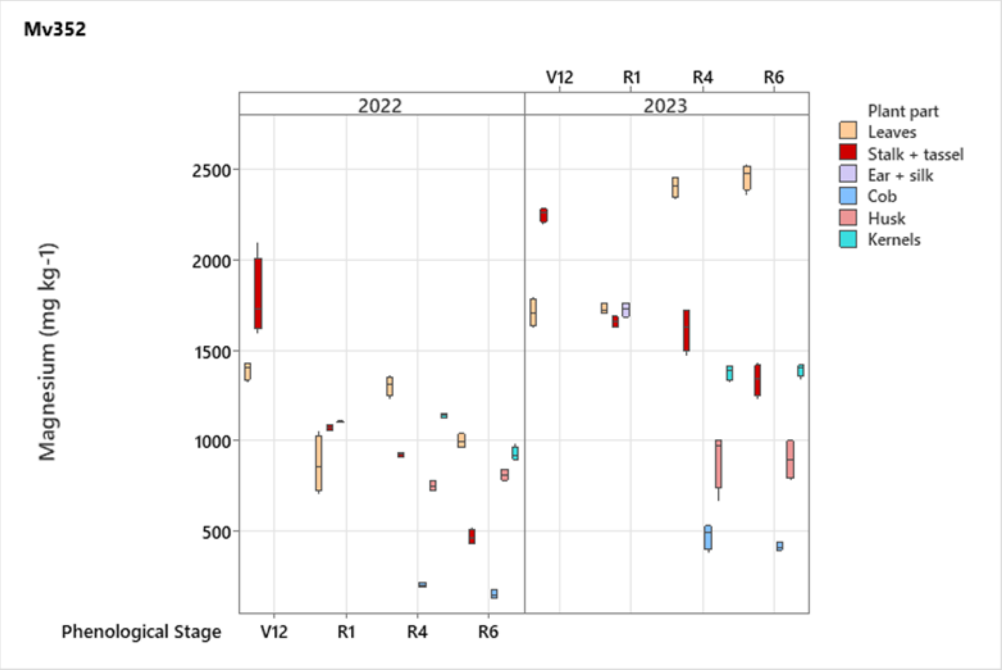

Figure 89. Magnesium accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage: p<0.01, Year*Hybrid, Hybrid*Plant Part and Year*Hybrid*Phenological Stage: p<0.05, Year*Plant Part: p<0.001. (Debrecen, 2022-2023).

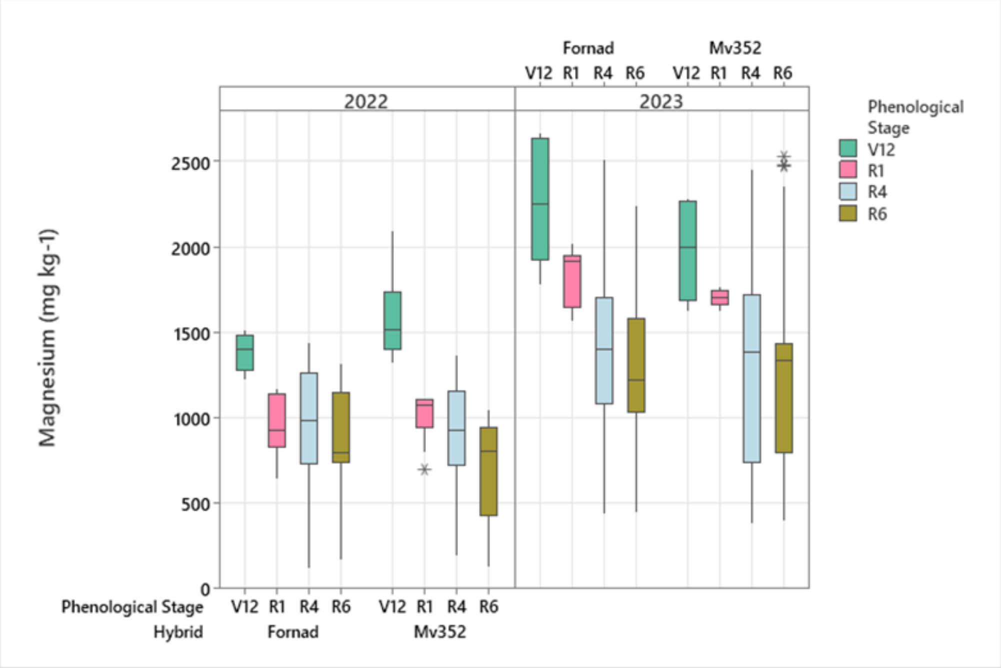

Figure 90. Magnesium accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage: p<0.01, Year*Hybrid, Hybrid*Plant Part and Year*Hybrid*Phenological Stage: p<0.05, Year*Plant Part: p<0.001. (Debrecen, 2022-2023).

Sulfur content was strongly affected by Year, Phenological Stage, and Plant Part (p<0.001). Hybrid had no significant effect as a main factor, but interactions like Year*Phenological Stage, Year*Hybrid, and Year*Hybrid*Phenological Stage were significant. Yet, based on our findings, Mv 352 accumulation of sulfur nutrient was slightly higher than that of Fornad (Figure 91, Figure 92). Sulfur accumulation was significantly higher in 2023 than in 2022 (Figure 93). The highest sulfur accumulation was at V12 and reduced towards R6 as would be anticipated due to its early uptake and redistribution. Leaves had the highest concentration since sulfur is used in protein synthesis as well as the activation of enzymes, which was many times higher than in the stalk. Kernels were the second organ after the leaves to have a high content of sulfur, while the cob had a low content of sulfur.

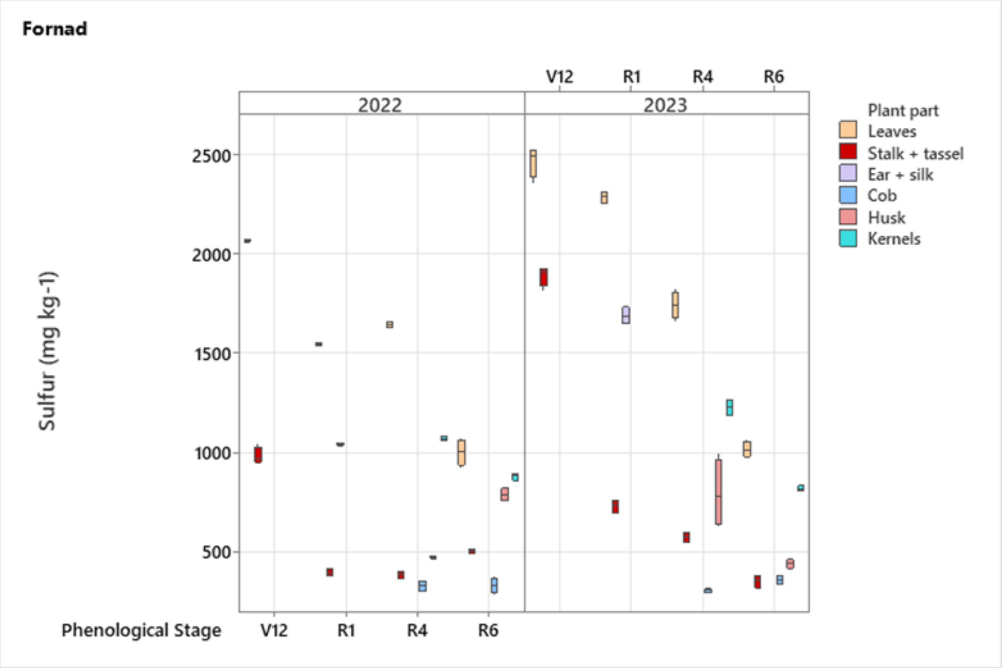

Figure 91. Sulfur accumulation within Fornad hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Year: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Year*Phenological Stage and Year*Hybrid: $p<0.001$, Year*Hybrid*Phenological Stage: $p<0.05$. (Debrecen, 2022-2023).

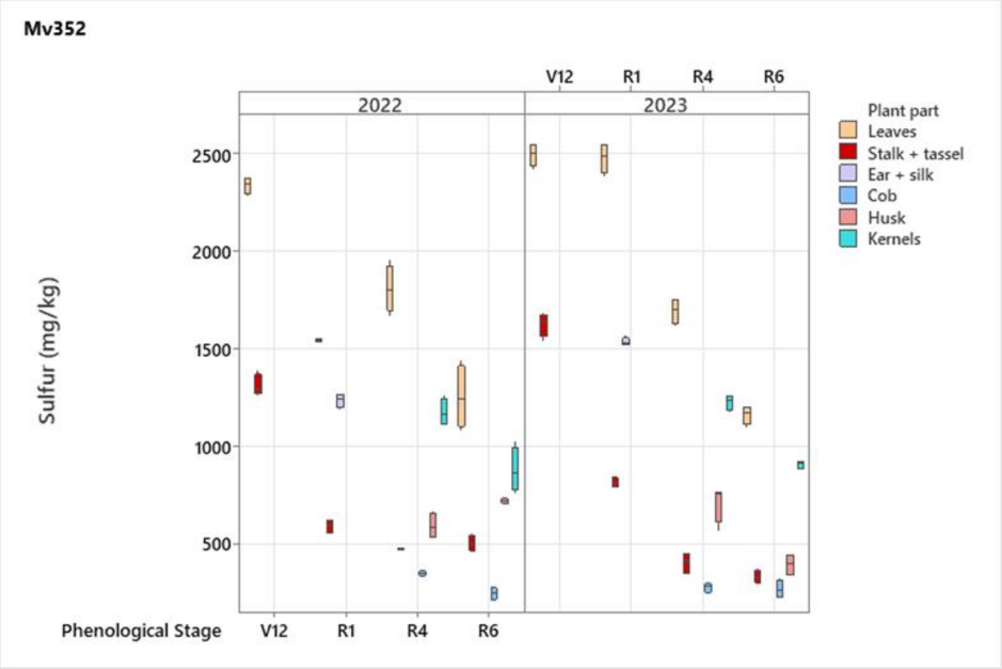

Figure 92. Sulfur accumulation within Mv 352 hybrid as a function of phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Year: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Year*Phenological Stage and Year*Hybrid: $p<0.001$, Year*Hybrid*Phenological Stage: $p<0.05$. (Debrecen, 2022-2023).

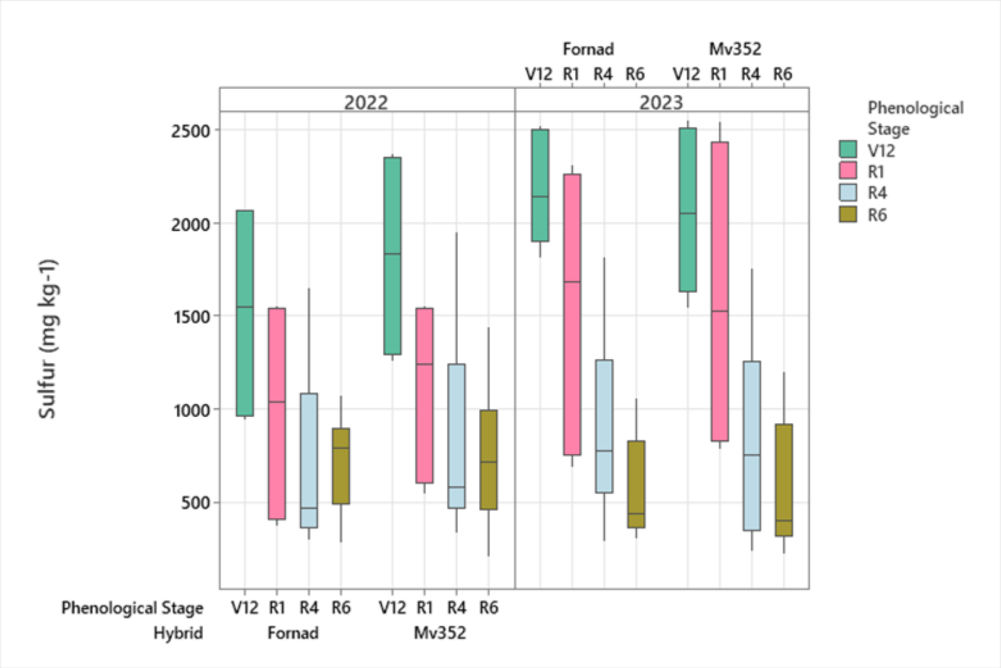

Figure 93. Sulfur accumulation in maize as a function of phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage and Year*Hybrid: p<0.001, Year*Hybrid*Phenological Stage: p<0.05. (Debrecen, 2022-2023).

Iron, manganese, boron, copper and zinc accumulation were all strongly influenced by the phenological stage and the parts of the plants (Appendix 5 and 6). Leaves consistently accumulated the highest concentrations due to their metabolic activity and vascular connectivity, whereas kernels and cobs showed the lowest levels, reflecting limited phloem mobility and low nutrient allocation to storage organs. Iron and copper levels declined from V12 to R1 before rising again at R6, whereas manganese and boron levels increased steadily towards R6 (with boron levels dipping slightly at R4). Zinc accumulated most at V12 and remained relatively stable afterwards. The year effects varied by nutrient, where, higher levels of iron, manganese, copper, and zinc were observed in 2023, while boron peaked in 2022. Hybrid effects were modest yet significant, where, Fornad accumulated higher levels of iron, boron, and zinc, whereas Mv 352 accumulated higher levels of manganese and slightly higher levels of copper. Significant interactions among year, phenological stage, plant part and hybrid indicated that nutrient dynamics were strongly regulated by environmental conditions and developmental processes.

- Plant height in two years 2022 and 2023 under irrigated conditions

Plant height was sensitive to phenological stage, hybrid type and environmental circumstances. This was statistically proven by the significant influence of phenological stage (p<0.001) and hybrid (p<0.01), and the interactions of

Year*Phenological Stage and Year*Hybrid on maize height. In 2023, maize plants appeared to be taller than in 2022, although the differences were not significant (Figure 95). Mv 352 showed greater height than Fornad (274.29 vs. 263.59 cm). Maize plant height reached its maximum at R1 and a minimum at V12 (Figure 94).

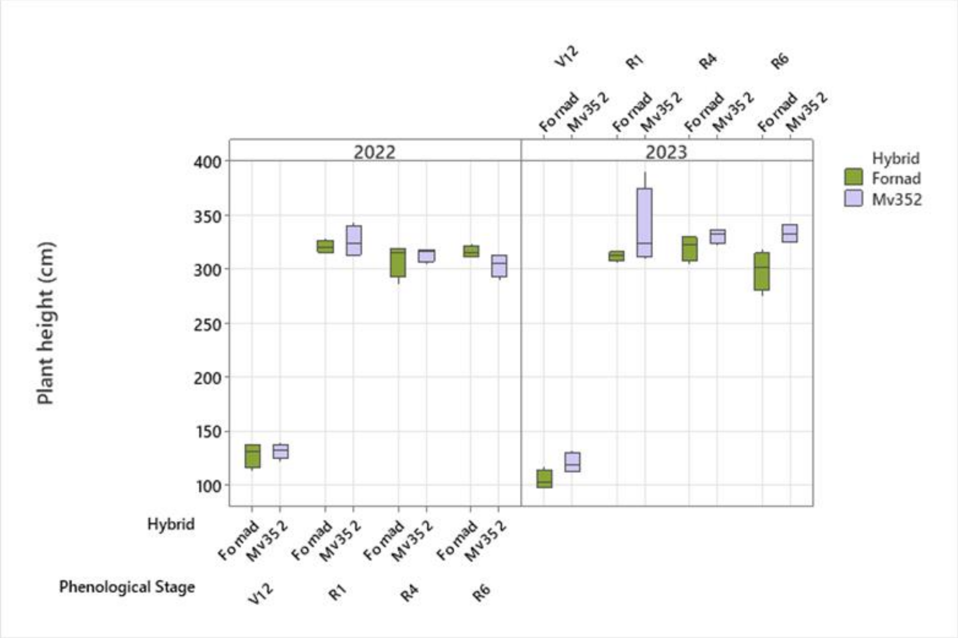

Figure 94. Maize plant height in response to phenological stages. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Year: ns | Interactions: Year*Phenological Stage: p<0.05, Year*Hybrid: p<0.01. (Debrecen, 2022-2023).

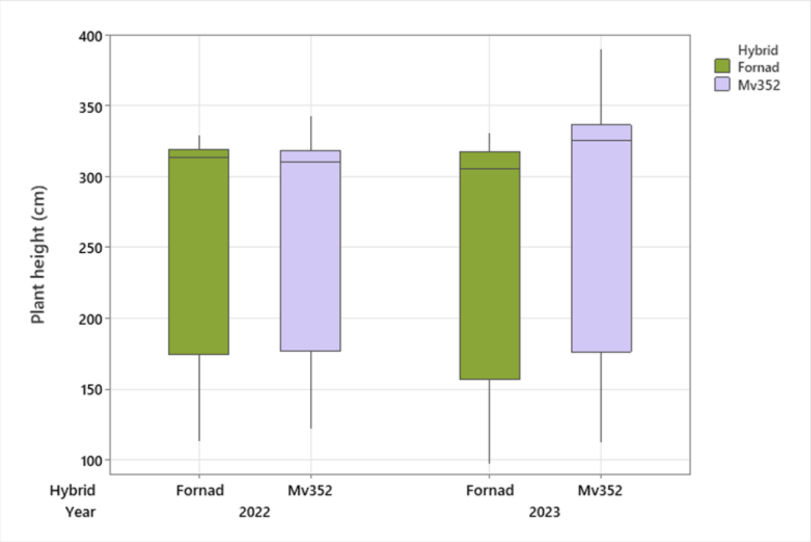

Figure 95. Maize plant height. Phenological Stage effect: p<0.001 | Hybrid: p<0.01 | Year: ns | Interactions: Year*Phenological Stage: p<0.05, Year*Hybrid: p<0.01. (Debrecen, 2022-2023).

4.3.2 Correlation analysis of two-year yield and the accumulated nutrient in maize under irrigated conditions, 2022-2023

Over the two-year period, Fornad yield was strongly linked to phosphorus, potassium, boron, iron, sulfur, and zinc and moderately linked to nitrogen uptake (Table 8). This is suggesting that these nutrients played a key role in supporting the plant's physiological processes during grain filling. This includes enhancing photosynthesis, nutrient transport, and overall grain development. However, there was a strong negative correlation between yield and calcium, copper, magnesium, and manganese. This is probably due to nutrient imbalances or toxicity, which prevented the plant from efficiently remobilizing nutrients into the kernels. This may disrupt grain fill and reduce the overall yield. Unlike Fornad, the yield of Mv 352 was strongly linked to nitrogen, phosphorus, potassium, and boron and moderately linked to calcium, copper, magnesium, and zinc. Additionally, there were small positive correlations between yield and manganese and sulfur and a negative relationship with iron.

Table 8. Correlations between maize yields and nutrient uptake under irrigated conditions. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p<0.05$. (Debrecen, 2022-2023).

	Fornad (2022-2023)	Mv 352 (2022-2023)
Nitrogen	0.05	**0.7**
Phosphorus	**0.8**	**0.71**
Potassium	**0.79**	**0.59**
Boron	**0.84**	**0.65**
Calcium	-0.84	**0.56**
Copper	-0.86	0.46
Iron	**0.8**	-0.23
Magnesium	-0.81	0.51
Manganese	-0.91	0.07
Sulfur	**0.81**	0.03
Zinc	**0.7**	0.4

4.3.3 Vegetative attributes response foliar fertilizer treatment, 2022-2023

- Soil Plant Analysis Development (SPAD)

The Year had a significant effect on SPAD ($p<0.001$), with 2023 showing overall higher values, this is likely due to more favorable environmental conditions (Figure 96). Hybrid and phenological stage were also significant contributors, while Treatment was not. However, the application of foliar nutrition resulted in an increase in SPAD values by 2.1% and 2.2% at R1 and R6, respectively, for Fornad in 2022. In the same year, the values recorded in Mv352 exhibited an increase of 3.4%, 2.4%, and 6.2% at V12, R1, and R6, respectively. The Tukey grouping revealed that SPAD was highest at R1 and R4 stages and lowest at R6 and V12. In addition, Mv 352 had higher SPAD values compared to Fornad.

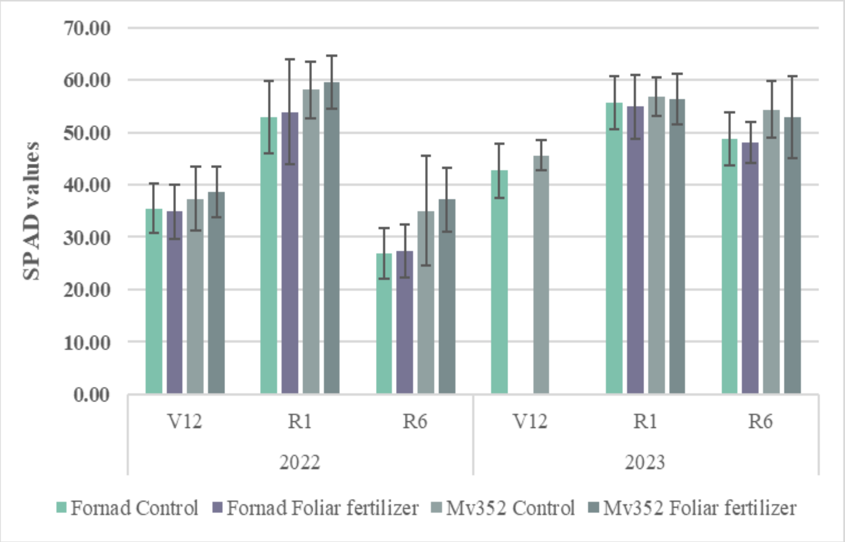

Figure 96. SPAD values of maize response to foliar fertilizers at different phenological stages under irrigated conditions. Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.001 | Treatment: ns | Interactions: ns. (Debrecen, 2022-2023).

- Normalised difference vegetation index (NDVI)

The Year effect was significant regarding NDVI (p<0.001), with the year 2023 outperforming 2022. Variation in phenological stage was significant, wherein NDVI was the highest at V12 and the lowest at R6 (Figure 97). Although the differences among the hybrids were not significant, Fornad had slightly better NDVI values across years and the growth stages, which reflected enhanced canopy development. The treatment effect was not significant, although, it led to an increase by 10.7% of NDVI values that were recorded in Mv 352 hybrid at R1 in 2022. Conversely, in the same year, it resulted in a decrease in NDVI values of Fornad hybrid at R6 by 29.8% as well as Mv 352 hybrid at R6 by 15%.

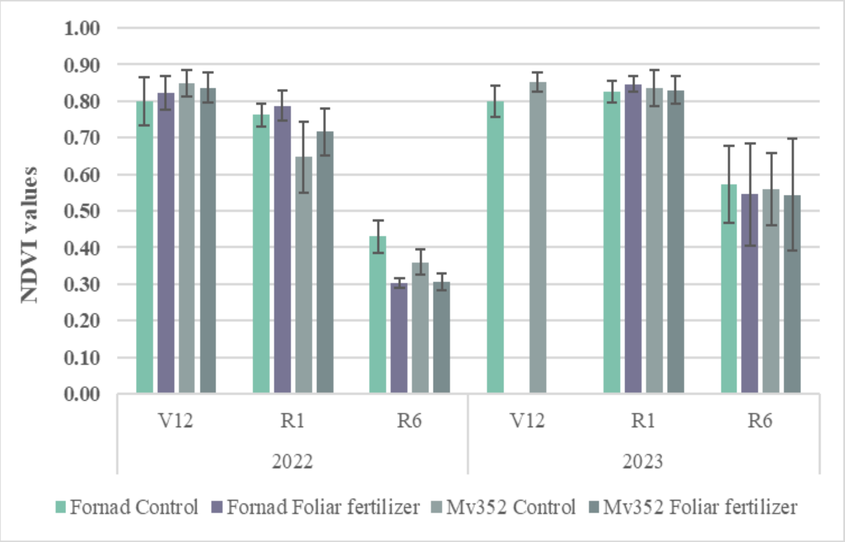

Figure 97. NDVI values of maize response to foliar fertilizers at different phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: ns | Year: $p<0.001$ | Treatment: ns | Interactions: Treatment*Phenological Stage: $p<0.001$, Hybrid* Phenological Stage, Year*Hybrid and Year*Treatment: $p<0.05$. (Debrecen, 2022-2023).

- Leaf area index (LAI)

The Year had a significant effect on LAI ($p<0.001$), where plants grown in 2023 had better canopy expansion than the ones grown in 2022 (Figure 98). In general, Mv 352 tended to have higher LAI values than Fornad ($p<0.05$). Additionally, the phenological stage affected also the maize LAI values ($p<0.001$), with maximum values at R1 and R4. These were further confirmed by the significant interaction of Hybrid*Phenological Stage, indicating that hybrids responded differently across the growth stages under irrigation.

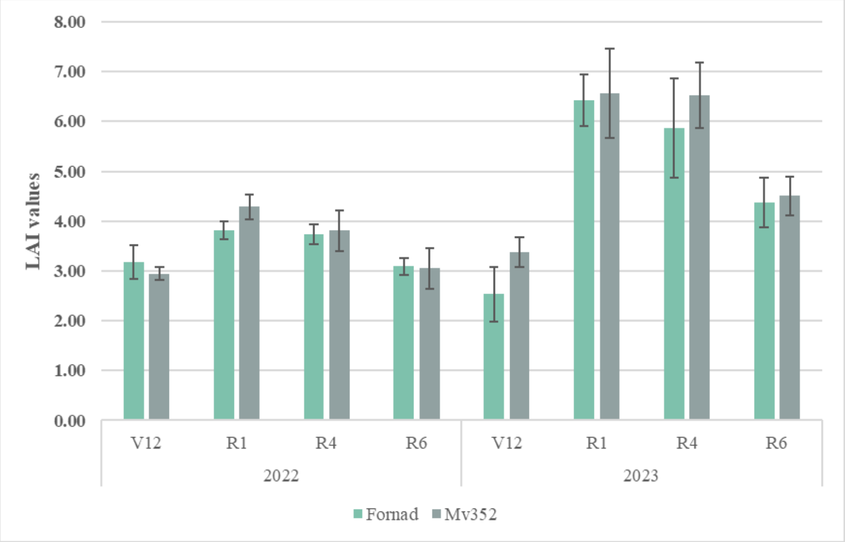

Figure 98. LAI values of maize at different phenological stages under irrigated conditions. Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Year: $p<0.001$ | Interactions: Year*Phenological Stage: $p<0.001$. (Debrecen, 2022-2023).

- Stem diameter

Stem diameter was significantly affected by hybrid (p<0.001) and by the Year*Hybrid and Year*Treatment*Hybrid (p<0.05) effects. Over the two seasons, Mv 352 had thicker stems than Fornad, which contributed to its better standability and capacity to carry heavier cobs (Figure 99). The treatment effect was not significant, but there was an evident influence of the foliar fertilization on stem diameter was evident. Additionally, it was observed that the stem was thicker in 2022 than in 2023. The variation in stem thickness between the hybrids across the years and treatments suggests a combination of genetic control and environmental sensitivity.

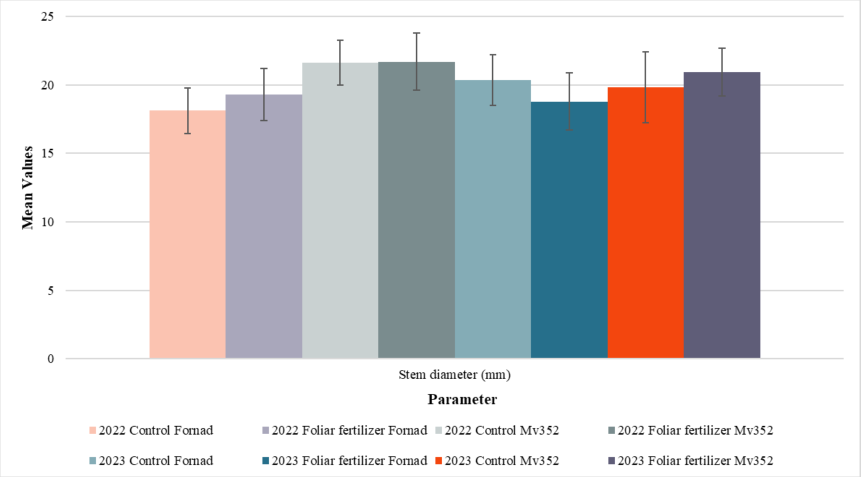

Figure 99. Maize stem diameter. Statistical significance was assessed using Tukey’s test at (p<0.05). (Debrecen, 2022-2023).

4.3.4 Grain quality traits response to foliar fertilizer treatment, 2022-2023

Grain moisture content was significantly influenced by hybrid (p<0.001) and treatment (p<0.05), while the year had no effect only when interacting with hybrid (p<0.001). During both seasons, Mv 352 recorded greater grain moisture content compared to Fornad, indicating delayed desiccation or improved water-holding capacity (Figure 100). Foliar application reduced moisture content, suggesting that excess nutrients could have accelerated physiological maturity or facilitated more efficient redistribution of moisture. The absence of year effect indicates that grain moisture reacted very uniformly across the two years of growth with drip irrigation. However, there was a slight decline in 2023. Oil content was significantly affected by year (p<0.05) with higher values in 2023 than in 2022. Neither hybrid nor treatment was significant. This implies moderate environmental control over oil biosynthesis, potentially temperature or photoperiod, rather than the influence of genotype and foliar fertilization. The relative stability of oil content between hybrids and treatments suggests that oil concentration is a genetically conserved trait unlikely to be altered by short-term management practices. Despite that, we could notice that higher oil content was observed in Mv 352 grains, and under the control plots. Protein content was significantly affected by hybrid ($p<0.001$), with greater protein content in Mv 352 than in Fornad for both years. Although the effect of the treatment was not significant, there was a tendency for the foliar fertilizer to increase protein content, especially in the case of the Fornad hybrid. There was no year or interaction effect, yet based on the results grain protein content was higher in 2023. These findings show that genetic background is the major determinant of protein accumulation, and foliar nutrition, if significant, would be a secondary influence. The higher protein in Mv 352 might be due to improved efficiency in nitrogen absorption or differential remobilization of nitrogen during grain development. Starch content was significantly affected by year ($p<0.001$) and hybrid ($p<0.001$). During the year 2023, there was a greater accumulation of starch in the hybrids under potentially more favorable conditions for carbohydrate synthesis or remobilization. Among the hybrids, Fornad produced grains that had invariably higher starch content, which reflects more intense allocation of photoassimilate towards carbohydrate reserve. Neither treatment nor interactions were significant, indicating that starch formation is likely more related to the genetic predisposition and environmental factors than with nutrient supplements. However, it was slightly higher under control plots.

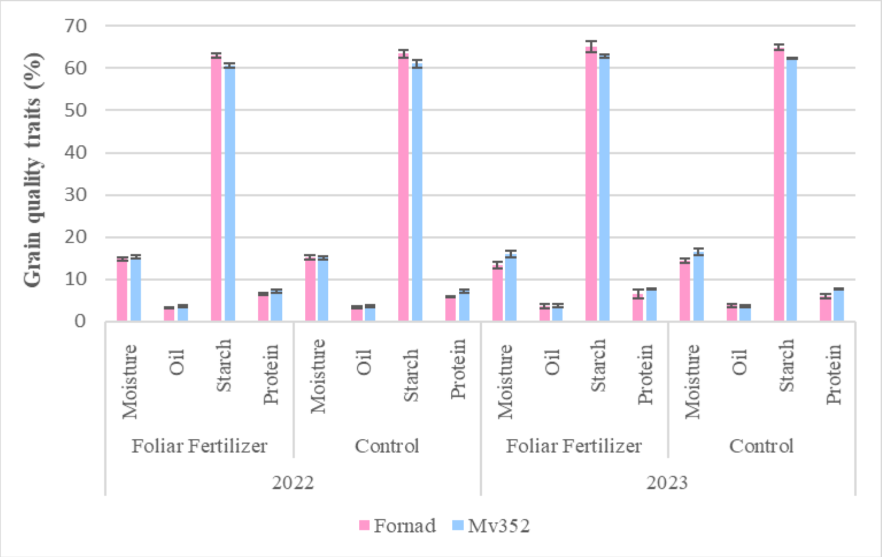

Figure 100. Grain quality traits of maize. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2022-2023).

4.3.5 Grain yield attributes response to foliar fertilizer treatment, 2022-2023

- Thousand grain weight, number of grains per cob, cob and grain weights

Thousand grain weight was strongly affected by hybrid ($p<0.001$). For instance, Mv 352 produced heavier grains than Fornad during the two seasons, once again confirming its advantage in grain-filling capacity (Figure 101). The grain weight in 2022 tended to be heavier, which can be attributed to more favorable grain-filling conditions. The lack of interaction or treatment effects indicate that, under these irrigated plots, grain weight is mostly controlled by genotype and hardly affected by short-term fertilization input. However, it was slightly higher under control plots. The number of grains per cob was found to be significantly affected by the hybrid type ($p<0.001$), with Fornad exhibiting a greater number of grains per cob by approximately 96.5 grains in comparison to Mv 352. Treatment*Hybrid ($p<0.001$) and the treatment also impacted the number of grains per cob ($p<0.05$), with an improvement of 6.3% observed over the two-year period. The Year effect was not significant, but the Year*Treatment*Hybrid interaction was ($p<0.001$), thereby reinforcing genotype-specific responses. In fact, based on our findings of this study, the number of grains per cob produced in 2022 was slightly higher than that produced in 2023. Hybrid ($p<0.001$), treatment ($p<0.05$), and interaction Treatment*Hybrid ($p<0.01$) significantly affected cob weight. Overall, Mv 352 had higher cob weight. Due to foliar fertilization, the cob weight of both hybrids increased between the two seasons, with the exception of the Mv 352 hybrid in 2023 that responded negatively to foliar fertilizer treatment. The grain weight was strongly affected by interactions including Year*Treatment ($p<0.05$) and Year*Treatment*Hybrid ($p<0.01$). These results highlight the sensitivity of grain weight to both environmental conditions and treatment-hybrid interactions. For instance, in 2022, Fornad responded greatly to foliar fertilization during stress, with grain weight increasing by 23.3%, while under optimal conditions, the same treatment decreased grain weight by 10%. This is a sign of a complex interplay between physiological and genetic responses to nutrient availability and environmental factors.

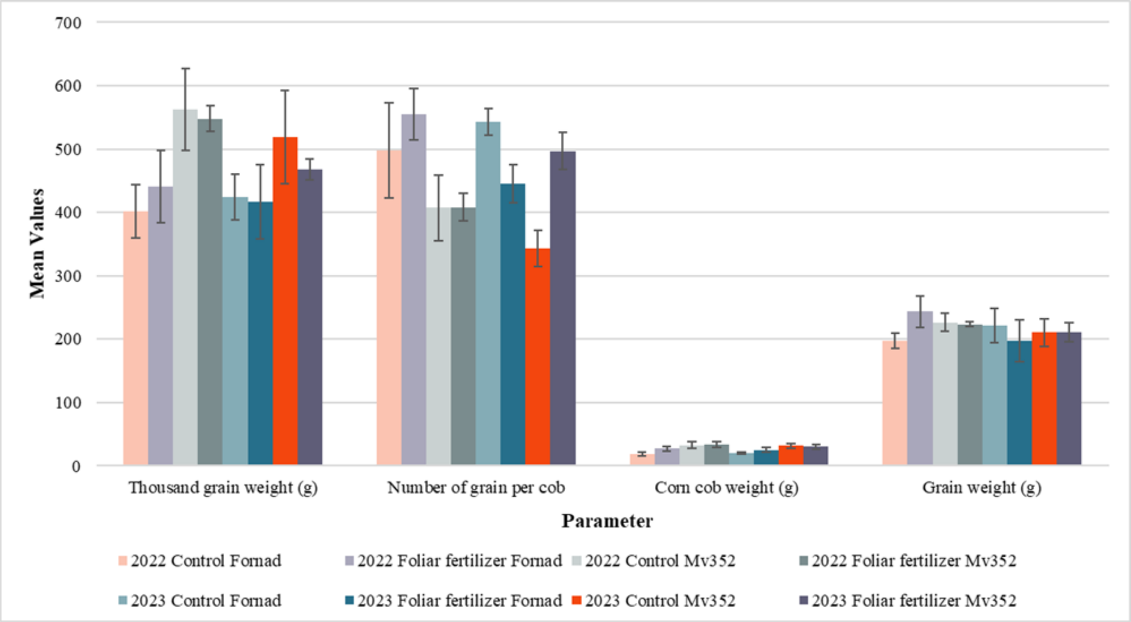

Figure 101. Maize grain attributes. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2022-2023).

- Ear length, ear height, ear weight and ear diameter

Ear length was significantly affected by hybrid ($p<0.001$), with Fornad having considerably longer ears than Mv 352 (Figure 102). This is proved throughout both years and treatments. Although the effect of treatment was not significant, there was evidence that longer ears resulted from foliar fertilization, with the exception of Mv 352 in 2022, where it responded negatively to foliar treatment, resulting in a slight reduction in its ear length. This suggests that ear length is primarily a genotype-controlled trait with limited plasticity in response to environmental factors under irrigation. Ear height, on the other hand, was significantly influenced by year, treatment, and hybrid ($p<0.001$), as well as their interactions, except Year*Treatment. The height of the ears was greater in 2023 compared to 2022, which may reflect more stem elongation under different environmental conditions. Mv 352 had a higher ear height than Fornad. Interestingly, foliar fertilization reduced the ear height, particularly in Mv 352, which may suggest a shift towards denser vegetative growth. Regarding ear weight, the Year*Treatment interaction and the three-way interaction Year*Treatment*Hybrid were significant ($p<0.05$). These complex interaction patterns suggest that foliar fertilization had interactive effects based on years and hybrids. Foliar nutrition resulted in a 25% increase in ear weight for Fornad hybrid in 2022. Despite the year effect being non significant, our findings indicate a general decrease in ear weight for both hybrids. Ear diameter was significantly influenced by hybrid ($p<0.05$) and by Year*Treatment, Year*Hybrid, and Year*Treatment*hybrid interactions. Mv 352 had greatly thicker ears. However, the interaction terms reveal that ear diameter differed enormously by season and foliar treatment, particularly in Fornad, whose ear diameter was significantly improved through foliar feeding in 2022, while it was reduced significantly by 4% in 2023. Overall, through the two seasons, foliar fertilizer treatment contributed to thicker ears in Mv 352. It was also observed that ear diameter was slightly higher in 2023, even though the difference was not significant.

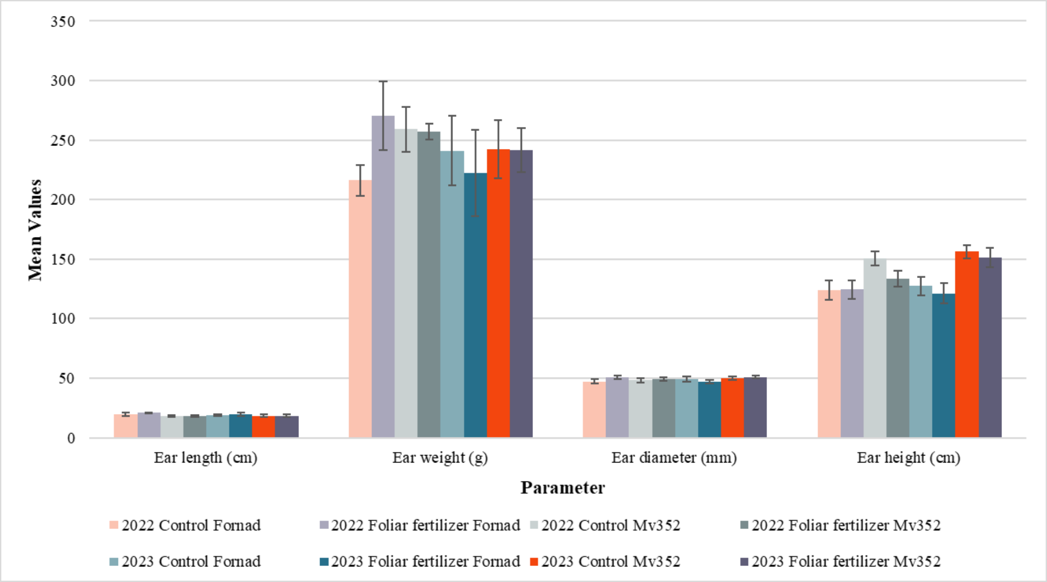

Figure 102. Maize ear characteristics. Statistical significance was assessed using Tukey's test at ($p<0.05$). (Debrecen, 2022-2023).

4.3.6 Grain yield between 2022 and 2023

The Year effect was significant ($p<0.01$), where 2022 had a slightly higher yield than 2023 (Figure 104). Nevertheless, 2022 was marked by prevailing drought conditions. This effect might have resulted from the prudent application of irrigation management during 2022, which coincided with major growth phases, thereby raising grain set and filling. Increased amount of radiation and thermal time accumulation in 2022 could have helped to compensate for the deficit water, thereby supplementing biomass and yield production. There is also a chance that genotype-specific resilience traits (particularly in Fornad) facilitated the efficient partitioning of assimilates under stress (Figure 103). Treatment ($p<0.001$) and hybrid ($p<0.001$) were highly significant. Overall, foliar fertilization increased yield by around 6% in comparison to the control. Among the two years of study, the highest yield was that of the Fornad hybrid under foliar fertilization, as opposed to Mv 352 (14.06 t ha^{-1} vs. 13.45 t ha^{-1}). The Year*Hybrid, Treatment*Hybrid, and Year*Treatment*Hybrid interactions were also significant, suggesting that the variation in crop yields over the years depends mainly on the crop genotype and the environment.

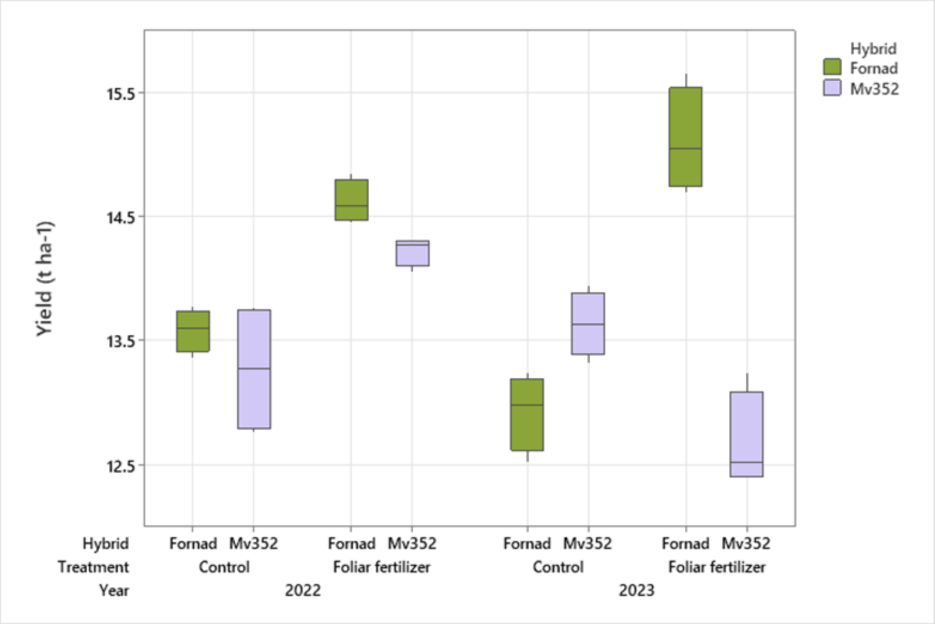

Figure 103. Maize yield response to foliar fertilization under irrigated conditions. Treatment effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.01 | Interactions: Treatment*Hybrid and Year*Treatment*Hybrid: p<0.001, Year*Hybrid: p<0.05. (Debrecen, 2022-2023).

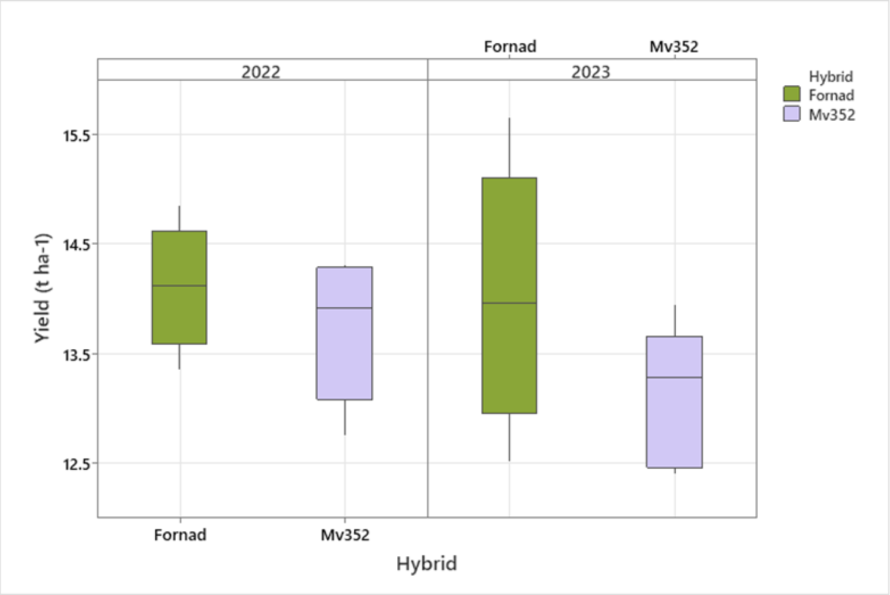

Figure 104. Maize yield under irrigated conditions. Treatment effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.01 | Interactions: Treatment*Hybrid and Year*Treatment*Hybrid: p<0.001, Year*Hybrid: p<0.05. (Debrecen, 2022-2023).

4.3.7 Correlation analysis between grain quality traits and yield, 2022-2023

Over the two-year period, Fornad's yield showed a strong positive correlation with protein content and a slight positive correlation with starch content (Table 9). Meanwhile, it displayed a strong negative correlation with oil content and a moderate negative correlation with moisture. In contrast, the Mv 352 hybrid demonstrated negative correlations between yield and starch, protein and oil content, with the correlation with starch content being particularly strong (Table 9). There was only a tiny, or even negligible, positive correlation with moisture content.

Table 9. Correlations between maize yield and grain quality traits under irrigated conditions. Values represent Pearson correlation coefficients (r). Significant correlations were defined as p<0.05. (Debrecen, 2022-2023).

	Moisture	Oil	Protein	Starch
Fornad 2022-2023	-039	-0.66	0.49	0.03
Mv 352 2022-2023	0.01	-0.24	-0.38	-0.70

5. Conclusions

The accumulation of dry matter and nutrients in the different plant organs were studied at different phenological stages. During early vegetative stages, the primary focus was on leaves and stalk growth. Accumulation, however, shifted towards the ears and kernels during the reproductive stages.

In 2022, Mv 352 accumulated greater dry biomass than Fornad at the end of the growing season (24476.05 kg ha^{-1} vs. 23092.83 kg ha^{-1}). Mv 352 also exhibited greater remobilization of essential nutrients to grains, such as N, P, Mg, S, and Zn (>50%), while Fornad remobilized N, S, and Zn similarly, and retained more nutrients in vegetative tissues. In 2023, without irrigation supply, nutrient uptake (N, P, K, B, Mg, Cu, Fe, Mn, S, and Zn) and plant height declined, while dry matter was less affected. Overall, under irrigated conditions, only remobilized N, P, Zn and S (only for Mv 352), contributed significantly to grain content (50% and above). Whereas, without irrigation, the remobilized N, P, Mg, Zn and S (for Fornad only), contributed significantly to grain content (50% and above). Partitioning of dry matter was significantly influenced by the use of irrigation, particularly in the case of the Fornad hybrid. This suggests that water availability is essential for sustained biomass development and assimilate allocation. Fornad hybrid accumulated 16432.81 kg ha^{-1} and 22680.45 kg ha^{-1} of dry matter in irrigated and non-irrigated conditions, respectively, at the maturity stage. Meanwhile, Mv 352 hybrid produced 23149.26 kg ha^{-1} and 20562.26 kg ha^{-1} in irrigated and non-irrigated conditions, respectively. This makes Mv 352 outperform Fornad in terms of dry biomass under irrigated conditions, while Fornad outperforms Mv 352 under non-irrigated conditions. Fornad hybrid was also found to absorb more nutrients, particularly under rainfed conditions, suggesting its drought tolerance and nutrient use efficiency compared to Mv 352. Over the two years, genotypic differences, however, was less pronounced than the effects of year/environmental factors.

Foliar fertilization slightly increased SPAD values in 2022, by up to 2.2% in Fornad and 6.2% in Mv 352. R1 stage holds the peak of SPAD and it was mainly higher in the Mv 352 hybrid. In 2023, SPAD values were significantly influenced by the water regime, the phenological stage, and the hybrid, with higher readings observed under irrigation and a peak at the R1 stage. Foliar fertilization had a significant impact on SPAD, particularly in Fornad hybrid under non-irrigated conditions, reflecting its chlorophyll stability and greater physiological adaptation to rainfed conditions.

During the two years, SPAD values were significantly higher in 2023, likely due to more favorable environmental conditions.

In 2022, Fornad slightly outperformed Mv 352 in NDVI, but the difference was minimal. NDVI was at its highest point at V12 and declined toward maturity. Foliar fertilization effect was minimal but Mv 352 showed a 10% NDVI increase at R1. Hybrid imposed a considerable effect on NDVI in the year 2023, where Mv352 was the greatest. NDVI generally peaked at V12 and R1. Foliar fertilization had no effect but resulted a marginal increase in NDVI in Fornad by 2.5% at R1 under irrigation and 1.9% at R1 and 6.5% at R6 under non-irrigated conditions. Over the two years, Year had a significant effect on NDVI, with higher values in 2023. While hybrid differences were not large, Fornad had a somewhat higher NDVI overall, indicating better canopy development.

Grain quality traits were hybrid-dependant. In 2022, Mv 352 had higher oil and protein content, while Fornad had more starch. In 2023, the water regime increased the oil and protein content of Mv 352 by 5.7% and 4.8%, respectively. Meanwhile, foliar fertilization increased the oil content of Mv 352 by 0.5% under irrigated conditions and by 4.5% under non-irrigated conditions, as well as the protein content of the Fornad hybrid by 10% under irrigation and the Mv 352 hybrid by 8% under non-irrigated conditions. Starch content was higher in Fornad, regardless of irrigation or foliar application. Over the two years, grain moisture was mainly controlled by hybrid and foliar treatment, with higher moisture in Mv 352 showing slowed drying. Oil content varied between years but remained constant among hybrids and treatments, exhibiting genetic control. Protein content was higher in Mv 352 and marginally increased by foliar fertilizer application, especially in Fornad. While, Year and hybrid influenced starch content, with Fornad having higher starch content.

Grain yield was influenced by hybrid, water regime and foliar fertilization. In 2022, Mv 352 yielded 13,273 t ha^{-1}, 312 kg less than Fornad. Foliar fertilization increased yields by 7.6% (14.62 t ha^{-1}) in Fornad and by 7.2% (14.23 t ha^{-1}) in Mv 352. In 2023, irrigation improved yields by 8.8% (13.59 vs. 12.48 t ha^{-1}). The foliar treatment significantly increased yield by 14%, with Fornad responding particularly well under rainfed conditions, where yield increased with 4.2 t ha^{-1}, compared to 2.2 t ha^{-1} under irrigation, demonstrating high stress adaptability. Over the two years, yields in 2022 were significantly higher likely due to timely irrigation, increased radiation, and/or thermal accumulation. Genotypic tolerance, particularly in Fornad, may have enabled adaptation to stress. Foliar fertilization also, enhanced yield by around 6%, with Fornad yielding 14.06 t ha^{-1} compared to 13.45 t ha^{-1} of Mv 352.

Overall, these results reveal the significant variations among the hybrids in terms of performance and productivity to irrigation and foliar nutrition under different weather conditions. Overall, owing to the difference in drought tolerance capacities of the studied hybrids, the yield performance of Fornad was better than Mv 352 under both environmental conditions. Fornad also outperformed Mv 352 with the application of foliar fertilization and exhibited higher nutrient uptake, especially under rainfed conditions. Our study highlights the importance of selecting the right hybrid, while adopting precision methods can offer a significant boost in maize productivity, improving remobilization traits and maximizing yield resilience in drought-prone or heat-stressed conditions.

6. New scientific results

1. Based on the comparative results during the two years with two different maize hybrids (Mv 352 and Fornad 420), it was concluded that under irrigation, Mv 352 accumulated greater dry biomass than Fornad at the end of the growing season (23813 kg ha^{-1} vs. 19763 kg ha^{-1}).

   In 2023, under irrigation, average accumulations of N, P and K were: 66.55 kg ha^{-1} (1.42 kg d^{-1} ha^{-1}), 14.59 kg ha^{-1} (0.31 kg d^{-1} ha^{-1}), and 122.65 kg ha^{-1} (2.61 kg d^{-1} ha^{-1}) from emergence up to V12; 71.95 kg ha^{-1}(3.43 kg d^{-1} ha^{-1}), 9.53 kg ha^{-1}(0.45 kg d^{-1} ha^{-1}), and 181.76 kg ha^{-1}(8.66 kg d^{-1} ha^{-1}) between V12 and R1; and 74.94 kg ha^{-1} (1.25 kg d^{-1} ha^{-1}), 20.70 kg ha^{-1}(0.35 kg d^{-1} ha^{-1}), and -72.2 kg ha^{-1} (-1.20 kg d^{-1} ha^{-1}) between R1 and the maturity, respectively. Wherease, under non-irrigation, average accumulations of N, P and K were: 62.74 kg ha^{-1}(1.34 kg d^{-1} ha^{-1}), 12.39 kg ha^{-1} (0.26 kg d^{-1} ha^{-1}), and 121.05 kg ha^{-1} (2.58 kg d^{-1} ha^{-1}) from emergence up to V12; 39.2 kg ha^{-1} (1.87 kg d^{-1} ha^{-1}), 5.68 kg ha^{-1}(0.27 kg d^{-1} ha^{-1}), and 114.52 kg ha^{-1}(5.45 kg d^{-1} ha^{-1}) between V12 and R1; and 95.92 kg ha^{-1} (1.6 kg d^{-1} ha−1), 19.6 kg ha^{-1}(0.33 kg d^{-1} ha^{-1}), and -45.76 kg ha^{-1} (-0.76 kg d^{-1} ha^{-1}) between R1 and the maturity, respectively.

2. Both hybrids remobilized N, P, S and Zn to the grain to a great extent (50% and above), while Mn (9%), Fe (6%), Ca (11%) and K (11%) were significantly different across the genotypes and remain predominantly in vegetative tissues (19-46%), resulting in limited remobilization.

3. Mv 352 responds reliably to irrigation, achieving 23149.26 kg ha^{-1} of dry matter under irrigated conditions, compared to 20562.26 kg ha^{-1} under non-irrigated conditions. In contrast, Fornad is more drought-resistant and exhibits higher nutrient uptake, especially under natural water supply conditions. Under non-irrigated conditions, it produced 22680.45 kg ha^{-1} of dry matter, which is almost 6 t ha^{-1} higher than the biomass produced under irrigated conditions (16432.81 kg ha^{-1}). Grain protein also differed significantly between the hybrids, with Mv 352 consistently producing more protein content than Fornad (7.5% vs 6.2%) over the years.

4. Over the two years, foliar fertilization increased yield by 6% under irrigated conditions. It was found that Fornad was more responsive, particularly when water availability is limited, as the foliar treatment significantly increased its yield by 4.2 t ha^{-1} (39% increase) under rain-fed conditions, compared to 2.2 t ha^{-1} (16.8% increase)

under irrigation, demonstrating high stress adaptability. Moreover, under non-irrigation, the ear and grain weights in Fornad increased by more than 30% as a result of foliar nutition, demonstrating its potential to offset stress-induced yield losses. Foliar nutrition also enhanced protein concentration, especially in the case of Fornad by 10% in both years under irrigated conditions.

7. Practical utilization of the new results

1. The Fornad hybrid showed significant benefits from foliar fertilization, enhancing drought tolerance and nutrient-use efficiency, making it ideal for resource-limited, drought-prone environments. It performs well with minimal irrigation and fertilization. In contrast, Mv 352 had higher nutrient needs, particularly nitrogen, for optimal protein formation. In this case, proper nitrogen management is crucial for yield and grain quality. Mv 352’s efficient fertilizer use, when applied correctly, requires tailored fertilization, especially in areas with consistent irrigation and nutrient availability. Understanding each hybrid's nutrient needs helps align fertilization practices to improve productivity and sustainability.
2. Foliar fertilization significantly increased Fornad’s ear and grain weights by more than 30% under non-irrigated conditions, while it increased seed set by 44.8% in Mv 352 under irrigated conditions. These results suggest that foliar nutrient supply is most beneficial when root uptake is limited, for example due to reduced water availability or when high-performing hybrids require rapid nutrient delivery during reproductive development. Thus, the application of foliar feeding prior the reproductive stage is an effective supplementary practice for stabilising yield in variable climates.
3. The results showed that nutrient uptake, especially of N, P and K, followed clear, stage-dependent patterns, with the highest accumulation occurring before flowering (V12-R1). This enables farmers to schedule fertilization and irrigation more efficiently by prioritising nutrient availability before and during the critical reproductive transition. Therefore, early-season monitoring, particularly of potassium (68-100% uptake before silking), ensures proper nutrient application, enhancing yield and grain quality.
4. Based on the results the two hybrids demonstrated contrasting nutrient use efficiencies. Fornad showed a strong reliance on nitrogen for yield formation, as well as better nutrient uptake under non-irrigated conditions. This makes it suitable for low-input and drought-prone areas due to its great stability and resilience. In contrast, Mv 352 exhibited higher overall nutrient demand and stronger correlations between macronutrients, micronutrients, and yield components, necessitating more precise and balanced fertilization. Understanding these hybrid-specific patterns helps to optimise fertilizer rates and reduce unnecessary nutrient losses.
5. The study revealed that Mv 352 performed best under favorable growing conditions, achieving a higher yield when the water supply is adequate. In contrast, Fornad outperformed Mv 352 under drought conditions. This emphasises the

importance of selecting a hybrid that is suited to the production environment and farm objectives in order to ensure yield stability under both optimal and water-limited conditions.

8. Summary

Maize, a cornerstone of global food security is facing increasing challenges in a changing world, in ever-changing population growth, shifting in dietery patterns, climate changes and the ongoing degradation of arable lands, threatening its essential role in food, feed, and bio-industrial supply chains. This two-year study investigated dry matter and nutrient accumulation of two maize hybrids (Fornad and Mv 352) across different phenological stages, under varying environmental conditions in order to understand the nutrient dynamics within the maize plant and their requierments at every phenological stage. Moreover, we evaluated the effect of precision drip irrigation and foliar fertilization on maize yield and grain yield attributes as well as grain quality traits, in comparaison with the control. During early vegetative stages, dry matter and essential nutrient are accumulated primarly in the leaves and stalk to promote their growth. As the plant grow, their uptake by the plant shifts towards the kernels during the reproductive stages. During the vegetative phase of the growing season, both hybrids incorporated significant amounts of mineral nutrients including N, P, K and Ca. When evaluating the effect of drip irrigation of the nutrient uptake dynamics, it has been found that it was not always positive effect at every growth stage of the plant. Overall, under irrigated conditions, only remobilized N, P, Zn and S (only for Mv 352), contributed significantly to grain content (50% and above). Drip irrigation has also positively affected maize vegetative parameters. On the other hand, foliar fertilization had minimal effect on NDVI but significantly positively influenced SPAD. Additionally, irrigation significantly increased plant height and yield by 4.3% and 19.9%. Foliar fertilization significantly improved yields by around 6%. The application of foliar nutrition, however, reduced the grain moisture, but increased protein content, even thought it wasn’t statistically significant. These findings underscore the significant differences in the response of the two hybrids to irrigation supply and foliar fertilization across different climatic conditions. Overall, Fornad consistently outperformed Mv 352 in terms of yield, both under irrigated and rainfed conditions, due to its greater drought tolerance and response to foliar fertilization.

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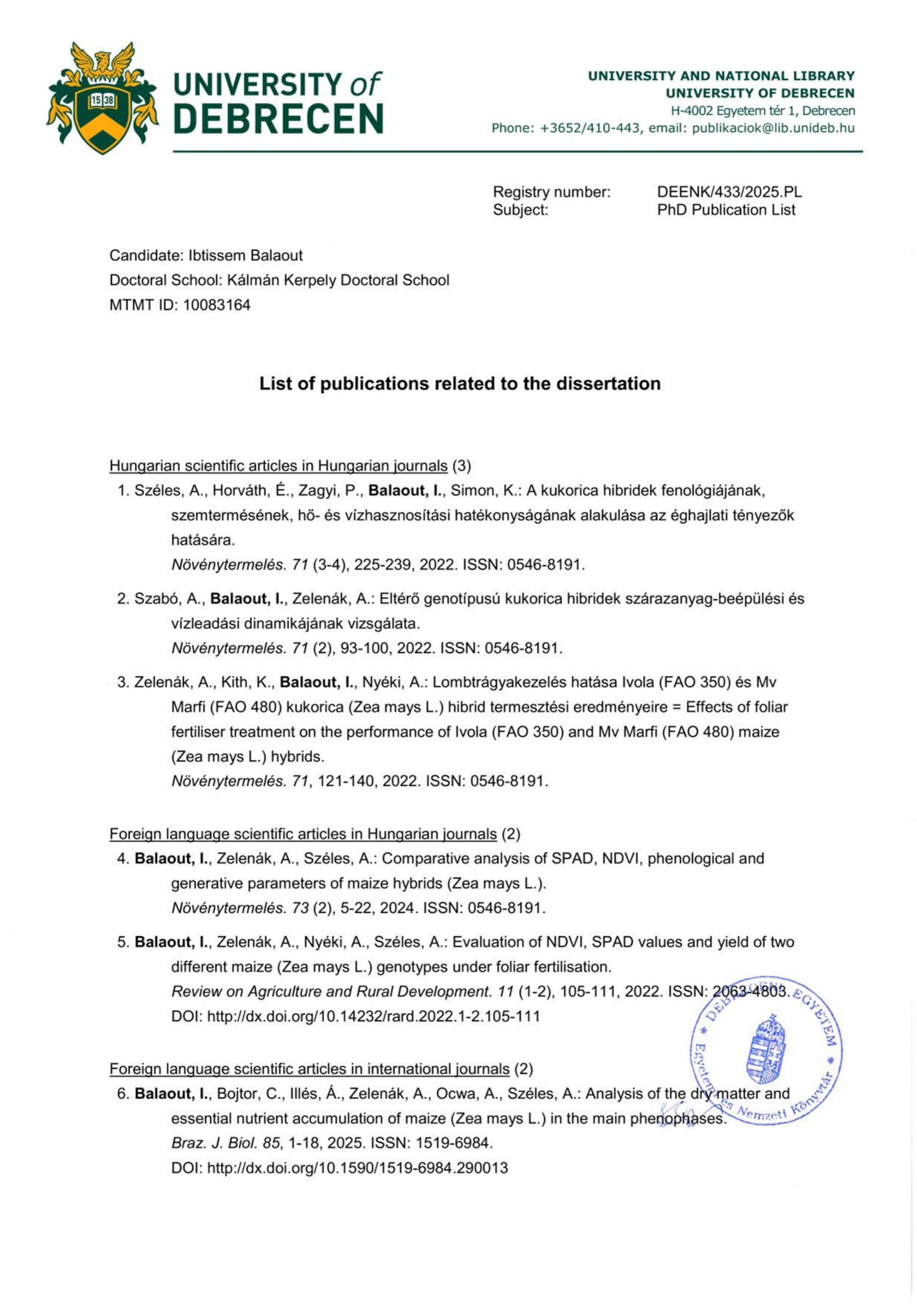
10. Publication list



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Subject:	PhD Publication List

Candidate: Ibtissem Balaout
Doctoral School: Kálmán Kerpely Doctoral School
MTMT ID: 10083164

List of publications related to the dissertation

Hungarian scientific articles in Hungarian journals (3)

1. Széles, A., Horváth, É., Zagyi, P., **Balaout, I.**, Simon, K.: A kukorica hibridek fenológiájának, szemtermésének, hő- és vízhasznosítási hatékonyságának alakulása az éghajlati tényezők hatására.
   Növénytermelés. 71 (3-4), 225-239, 2022. ISSN: 0546-8191.
2. Szabó, A., **Balaout, I.**, Zelenák, A.: Eltérő genotípusú kukorica hibridek szárazanyag-beépülési és vízleadási dinamikájának vizsgálata.
   Növénytermelés. 71 (2), 93-100, 2022. ISSN: 0546-8191.
3. Zelenák, A., Kith, K., **Balaout, I.**, Nyéki, A.: Lombtrágyakezelés hatása Ivola (FAO 350) és Mv Marfi (FAO 480) kukorica (Zea mays L.) hibrid termesztési eredményeire = Effects of foliar fertiliser treatment on the performance of Ivola (FAO 350) and Mv Marfi (FAO 480) maize (Zea mays L.) hybrids.
   Növénytermelés. 71, 121-140, 2022. ISSN: 0546-8191.

Foreign language scientific articles in Hungarian journals (2)

4. **Balaout, I.**, Zelenák, A., Széles, A.: Comparative analysis of SPAD, NDVI, phenological and generative parameters of maize hybrids (Zea mays L.).
   Növénytermelés. 73 (2), 5-22, 2024. ISSN: 0546-8191.
5. **Balaout, I.**, Zelenák, A., Nyéki, A., Széles, A.: Evaluation of NDVI, SPAD values and yield of two different maize (Zea mays L.) genotypes under foliar fertilisation.
   Review on Agriculture and Rural Development. 11 (1-2), 105-111, 2022. ISSN: 2063-4803.
   DOI: http://dx.doi.org/10.14232/rard.2022.1-2.105-111

Foreign language scientific articles in international journals (2)

6. **Balaout, I.**, Bojtor, C., Illés, Á., Zelenák, A., Ocwa, A., Széles, A.: Analysis of the dry matter and essential nutrient accumulation of maize (Zea mays L.) in the main phenophases.
   Braz. J. Biol. 85, 1-18, 2025. ISSN: 1519-6984.
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7. Ocwa, A., Bojtor, C., Illés, Á., Ssemugenze, B., **Balaout, I.**, Rátonyi, T., Széles, A., Harsányi, E.: Precision drip Irrigation System and Foliar Application of Biostimulant and Fertilizers Containing Micronutrients Optimize Photochemical Efficiency and Grain Yield of Maize (Zea mays L).
   J Soil Sci Plant Nutr. 24, 7786-7800, 2024. ISSN: 0718-9508.
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Foreign language abstracts (8)

8. Ocwa, A., Ssemugenze, B., Kuunya, R., Gumisiriya, C., **Balaout, I.**, Bojtor, C., Illés, Á., Harsányi, E.: Improving the agronomic performance of maize: differential responses to precision irrigation.
   In: Proceedings of the Plants 2025: From Seeds to Food Security, Sciforum MDPI, Barcelona, 1, 2025, (Plants 2025 Conference, ISSN 2223-7747 ; 2025)

9. **Balaout, I.**, Ocwa, A., Zelenák, A., Bojtor, C., Illés, Á., Széles, A.: Response of maize yield, dry matter and nutrient accumulation to drip irrigation: a sustainable approach to food security.
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10. Zagyi, P., Horváth, É., Simon, K., **Balaout, I.**, Juhász, C., Széles, A.: Dynamics of maize emergence, development and yield at different sowing times.
    In: 2nd International Congress on Sustainable Development in the Human Environment - Current and Future Challenges : Proceedings book. Eds.: Atilgan Atilgan, Iksad Institute, Antalya, 9, 2024. ISBN: 9786258254600

11. **Balaout, I.**, Bojtor, C., Zelenák, A., Zagyi, P., Széles, A.: Evaluation of maize (Zea mays L.) essential nutrients dynamic during its developmental phenophases.
    In: 8th Cereals and Europe Spring Meeting : Book of Abstracts / Peter Weegels, Dubravka Novotni, Artion Conferences and Events, Zagreb, 68, 2024.

12. Széles, A., Horváth, É., Zagyi, P., **Balaout, I.**, Simon, K.: Development of the phenology, heat and water use efficiency and grain yield of maize hybrids in a moderately hot, dry production zone.
    In: International Congress on Sustainable Development in the Human Environment- Current & Future Challenges ICSDEC 2022 : Proceedings book. Eds.: Anna Krakowiak-Bal, Atilgan Atilgan, Roman Rolbiecki, Hakan Aktas, Infrastructure and Ecology of Rural Areas Association, Krakow, 253, 2022. ISBN: 9788396606211

13. **Balaout, I.**, Zelenák, A., Nyéki, A.: Evaluation of NDVI, SPAD values and yield of two different maize (Zea mays L.) genotypes under foliar fertilisation.
    In: 19th Wellmann International Scientific Conference : Book of abstract. Ed.: Kiss Orsolya, University of Szeged Faculty of Agriculture, Hódmezővásárhely, 23, 2022. ISBN: 29789633068601

14. Zagyi, P., Tamás, A., **Balaout, I.**, Horváth, É., Simon, K., Széles, A.: Examination of the effect of basal fertilization and top-dressing on the vegetation index values and yield of maize hybrids of different genotypes.
    In: International Congress on Sustainable Development in the Human Environment- Current & Future Challenges ICSDEC 2022 : Proceedings book. Eds.: Anna Krakowiak-Bal, Atilgan Atilgan, Roman Rolbiecki, Hakan Aktas, Infrastructure and Ecology of Rural Areas Association, Krakow, 229, 2022. ISBN: 9788396606211
15. **Balaout, I.**, Zelenák, A., Szabó, A., Bojtor, C.: Maize (Zea mays L.) productivity response to foliar fertilisation under different environmental conditions.
    In: International Congress on Sustainable Development in the Human Environment - Current & Future Challenges ICSDEC 2022 : Proceedings book. Eds.: Anna Krakowiak-Bal, Atilgan Atilgan, Roman Rolbiecki, Hakan Aktas, Infrastructure and Ecology of Rural Areas Association, Krakow, 255, 2022. ISBN: 9788396606211

List of other publications

Foreign language scientific articles in Hungarian journals (1)

16. **Balaout, I.**, Kovács, G., Tuba, G., Zsembeli, J.: Effect of sufficient and deficit irrigation with different salt inputs on the yield of cucumber.
    Acta agrar. Debr. 2023 (2), 19-25, 2023. ISSN: 2416-1640.
    DOI: http://dx.doi.org/10.34101/ACTAAGRAR/2/12421

Total IF of journals (all publications): 3,1
Total IF of journals (publications related to the dissertation): 3,1

The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

02 July, 2025

11. Acknowledgment

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12. Declaration

I prepared this dissertation within the framework of the Kálmán Kerpely Doctoral School of University of Debrecen, for the purpose of obtaining a doctoral degree (Ph.D.) at the University of Debrecen.

Debrecen, 20.........................

signature of the candidate

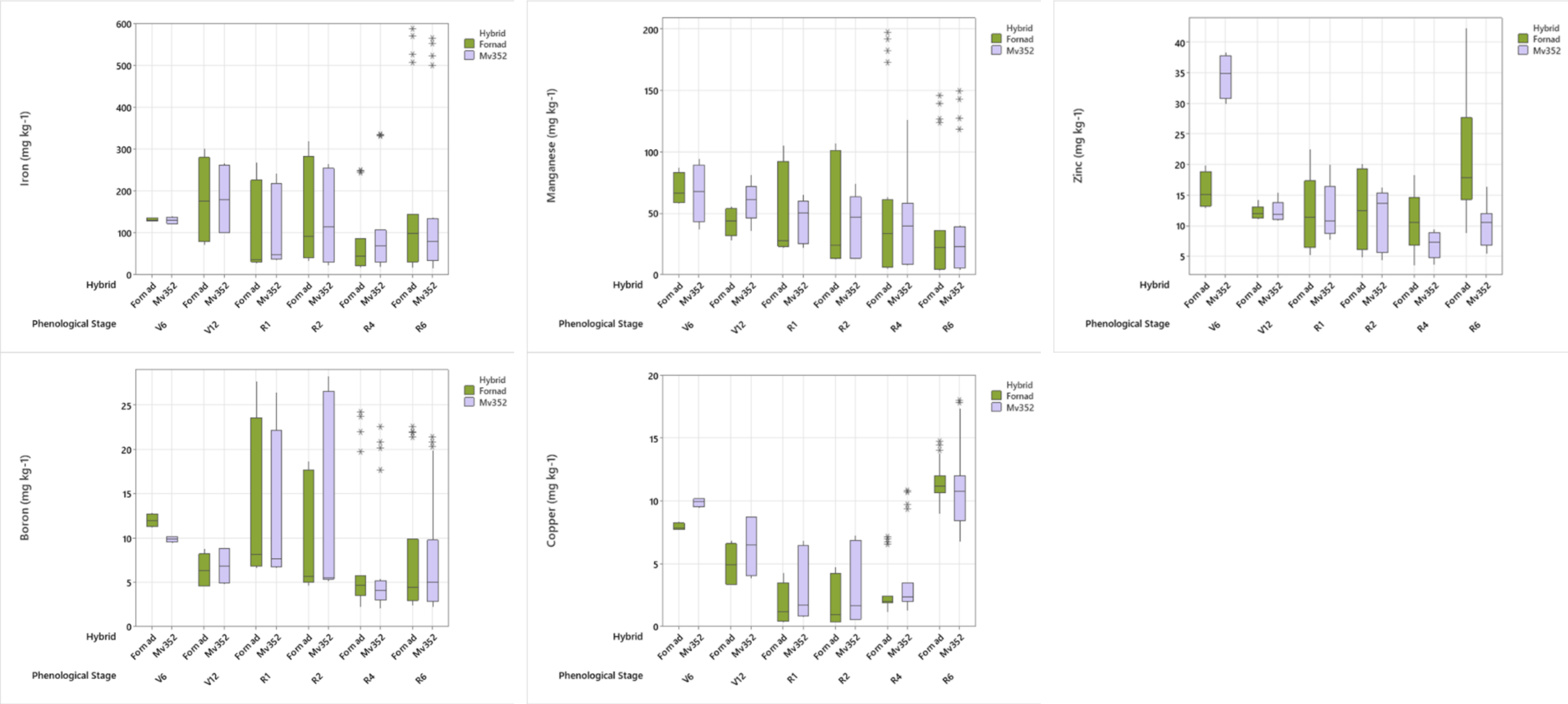
Declaration

I hereby certify that **Ibtissem Balaout**; a doctoral candidate between 2021-2026, and within the framework of the above-mentioned Doctoral School carried out her work under my guidance/direction. The candidate has made a decisive contribution to the results of the thesis through her independent creative work, and the thesis is the candidate's independent work. I recommend that the thesis be accepted.

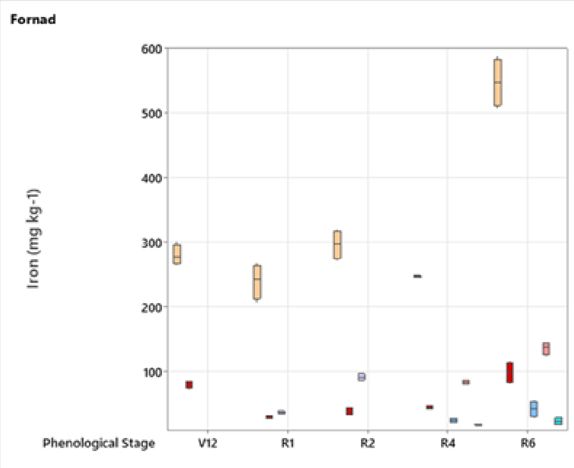
Debrecen, 20...............................

signature of the supervisor

13. List of appendix



Appendix 1. Micronutrients uptake of maize as a function of phenological stages under irrigated conditions. **Fe**:Phenological Stage effect: ns | Hybrid: ns | Interaction: ns. **Mn**: Phenological Stage effect: ns | Hybrid: ns | Interaction: ns. **B**: Phenological Stage effect: $p<0.05$ | Hybrid: ns | Interaction: ns. **Cu**: Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.05$ | Interaction: ns. **Zn:** Phenological Stage effect: $p<0.001$ | Hybrid: ns | Interaction: $p<0.001$. (Debrecen, 2022).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300
200
100
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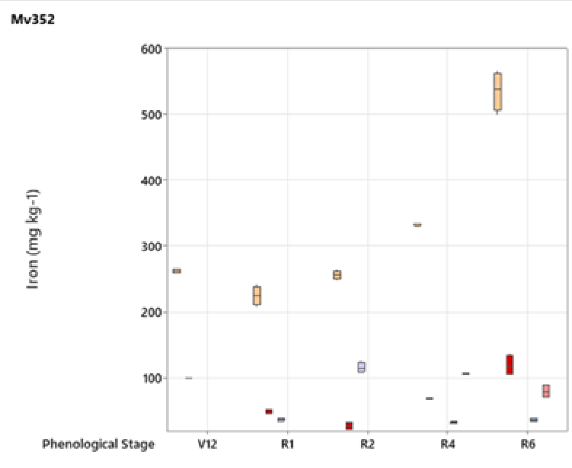
R1
R2
R4
R6


Mv352
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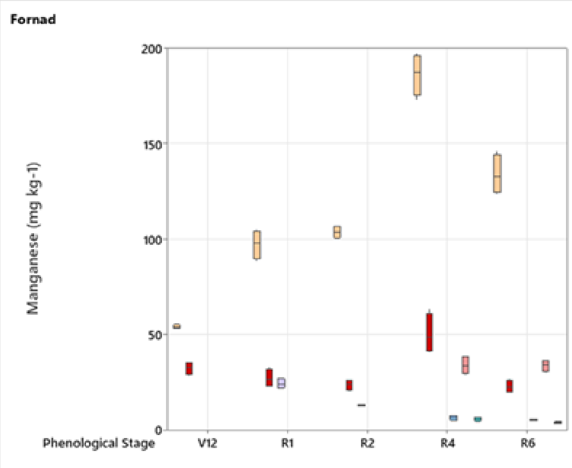
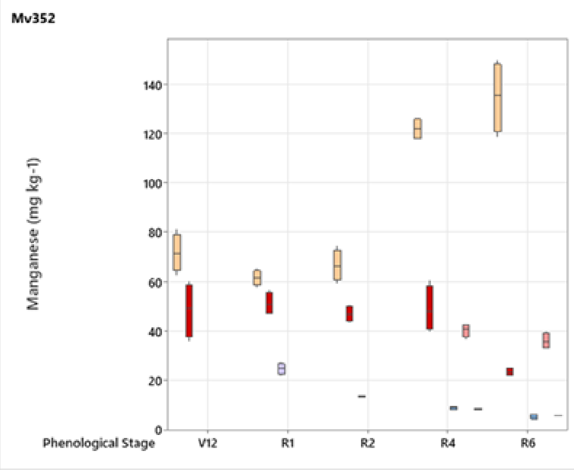
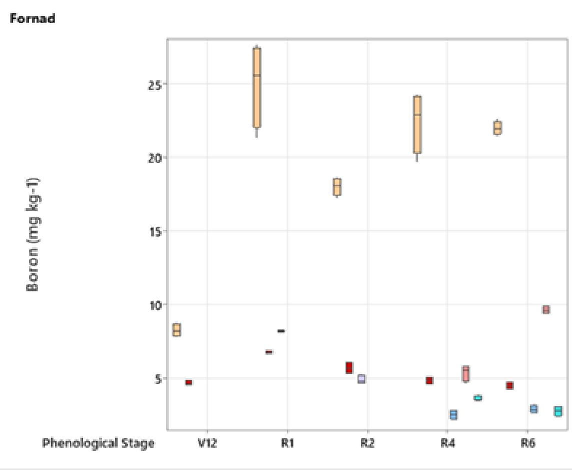
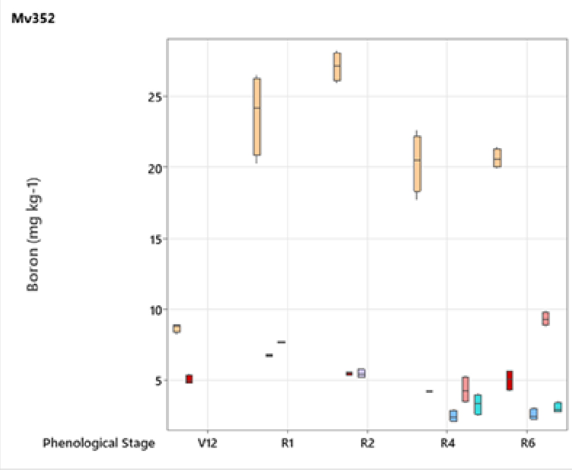
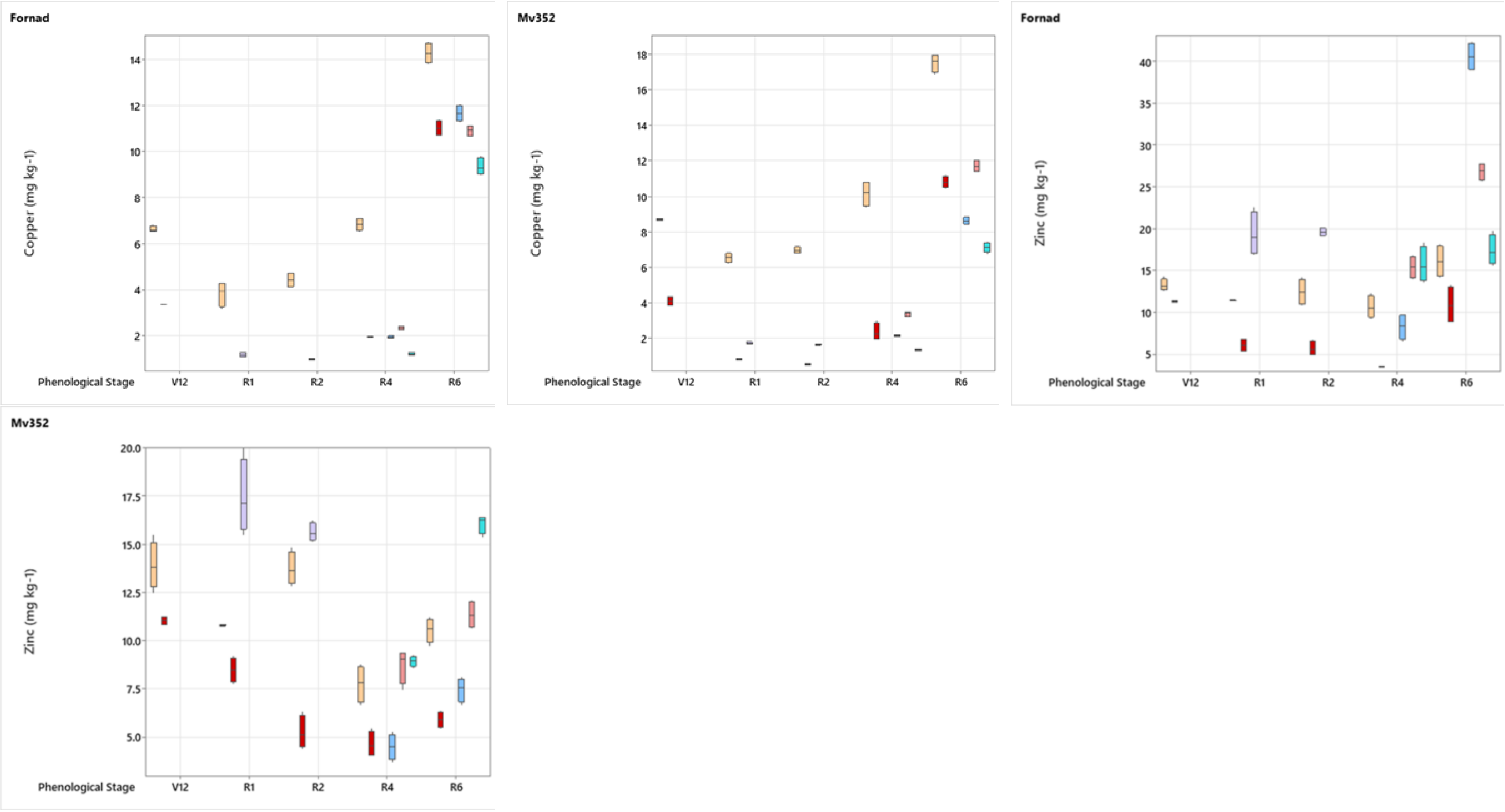
300
200
100
Phenological Stage
V12
R1
R2
R4
R6


Fornad
Manganese (mg kg-1)
200
150
100
50
0
Phenological Stage
V12
R1
R2
R4
R6

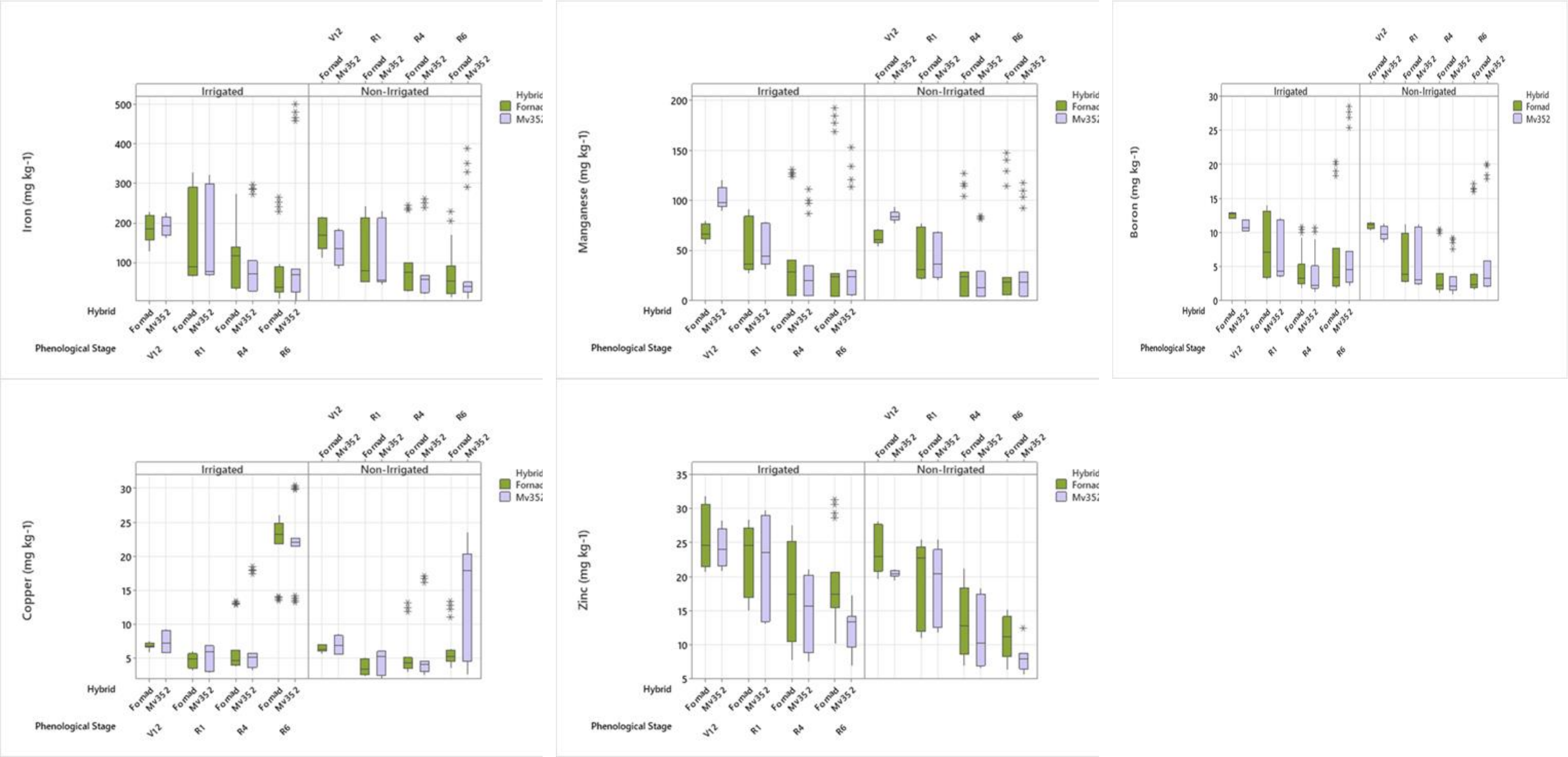

Mv352
Manganese (mg kg-1)
140
120
100
80
60
40
20
0
Phenological Stage
V12
R1
R2
R4
R6


Fornad
Boron (mg kg-1)
25
20
15
10
5
Phenological Stage
V12
R1
R2
R4
R6

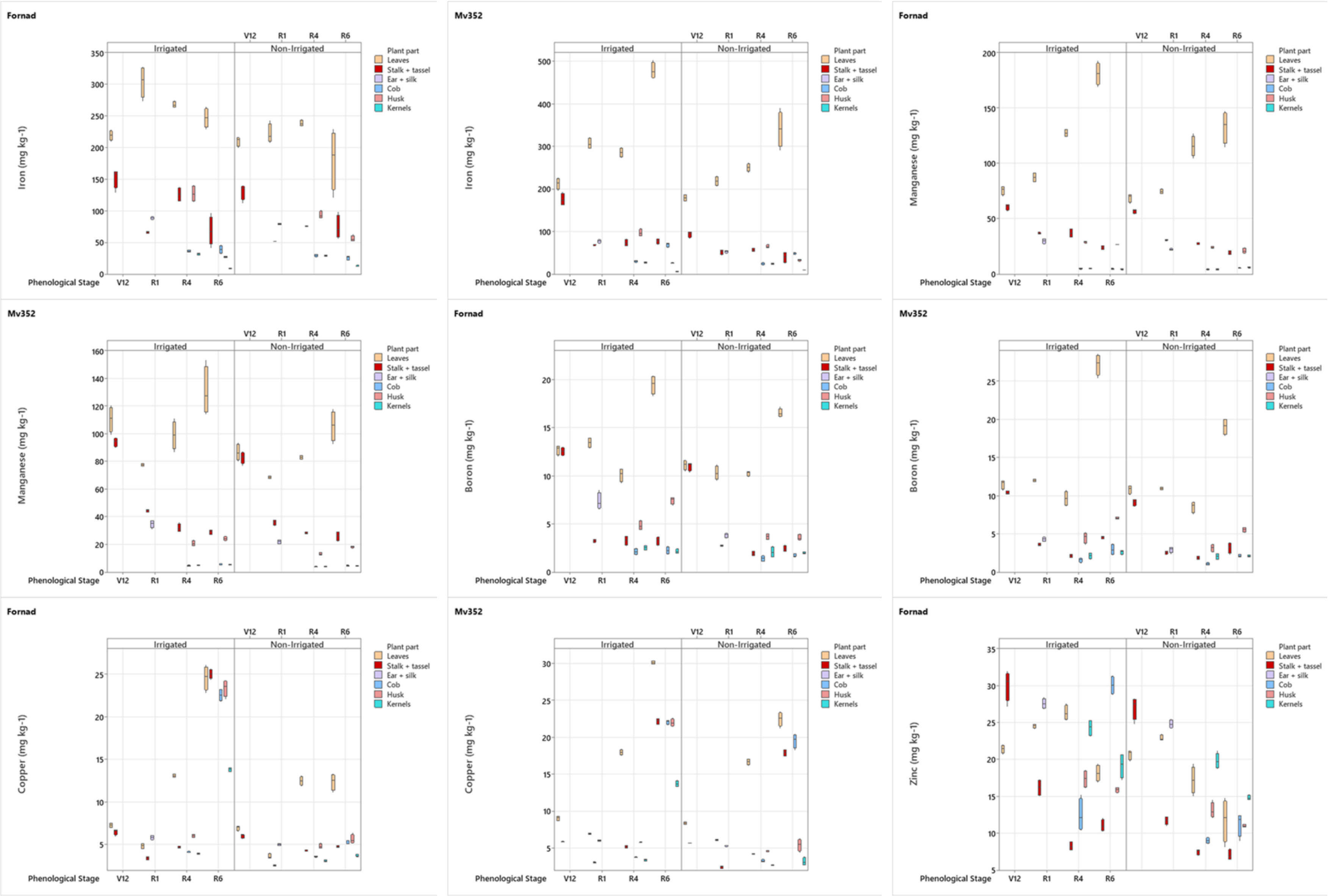

Mv352
Boron (mg kg-1)
25
20
15
10
5
Phenological Stage
V12
R1
R2
R4
R6

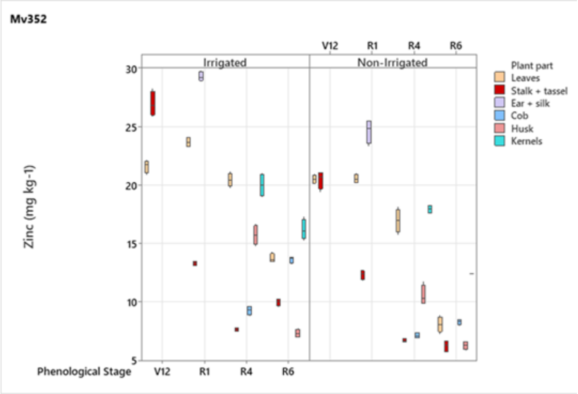


Appendix 2. Micronutrients uptake of maize as a function of phenological stages under irrigated conditions. **Fe:** Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: ns. **Mn:** Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: Hybrid*Phenological Stage: $p<0.05$, Hybrid*Plant Part: $p<0.001$. **B:** Phenological Stage effect: $p<0.001$ | Hybrid: ns | Plant Part: $p<0.001$ | Interactions: Hybrid*Phenological Stage: $p<0.05$. **Cu:** Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.01$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: $p<0.001$. **Zn:** Phenological Stage effect: $p<0.001$ | Hybrid: $p<0.001$ | Plant Part: $p<0.001$ | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: $p<0.001$. (Debrecen, 2022).

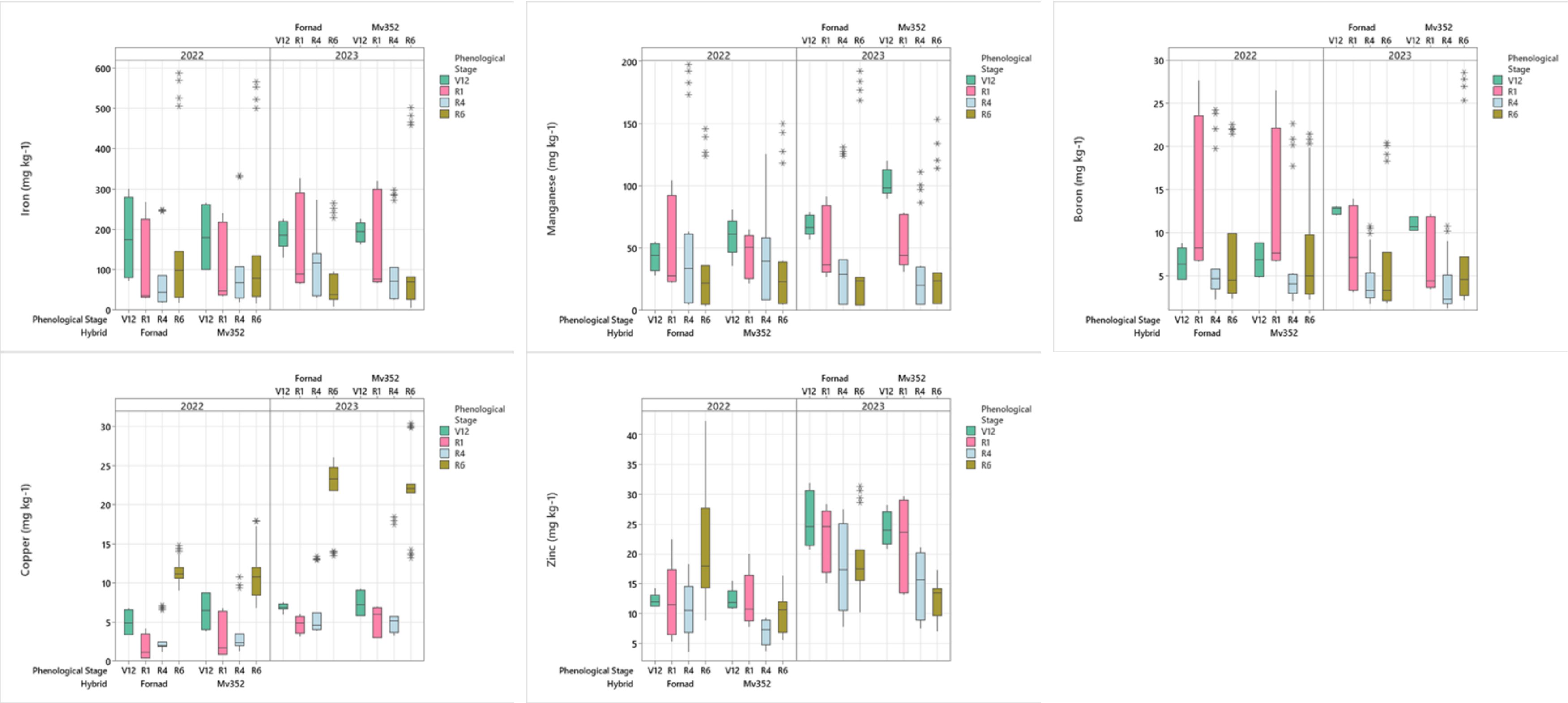


Appendix 3. Micronutrients uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. **Fe**: Phenological Stage effect: ns | Hybrid: ns | Treatment: p<0.01 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001, Treatment*Plant Part: p<0.01. **Mn**: Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Treatment: p<0.05 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage, Hybrid*Plant Part: p<0.001. **B**: Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.01 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.05. **Cu:** Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage, Hybrid*Plant Part, Treatment*Phenological Stage and Treatment*Hybrid*Phenological Stage: p<0.001, Treatment*Plant Part and Treatment*Hybrid*Plant Part: p<0.01. **Zn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).

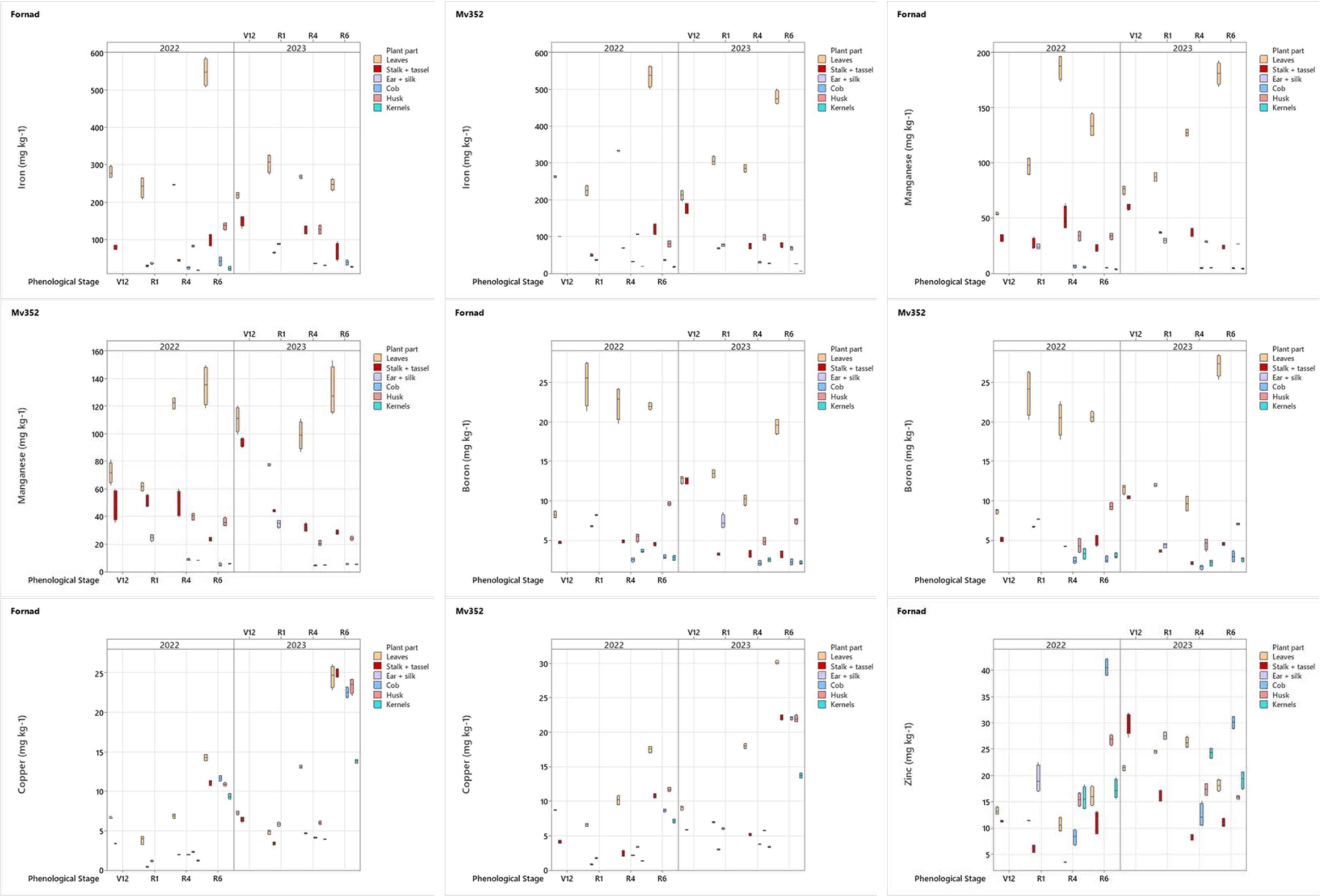

Fornad
Iron (mg kg-1)
0
50
100
150
200
250
300
350
Irrigated
Non-Irrigated
V12
R1
R4
R6
Phenological Stage
Plant part
Leaves
Stalk + tassel
Ear + silk
Cob
Husk
Kernels
Mv352
Iron (mg kg-1)
0
100
200
300
400
500
Fornad
Manganese (mg kg-1)
0
50
100
150
200
Mv352
Manganese (mg kg-1)
0
20
40
60
80
100
120
140
160
Fornad
Boron (mg kg-1)
0
5
10
15
20
Mv352
Boron (mg kg-1)
0
5
10
15
20
25
Fornad
Copper (mg kg-1)
5
10
15
20
25
Mv352
Copper (mg kg-1)
5
10
15
20
25
30
Fornad
Zinc (mg kg-1)
5
10
15
20
25
30
35

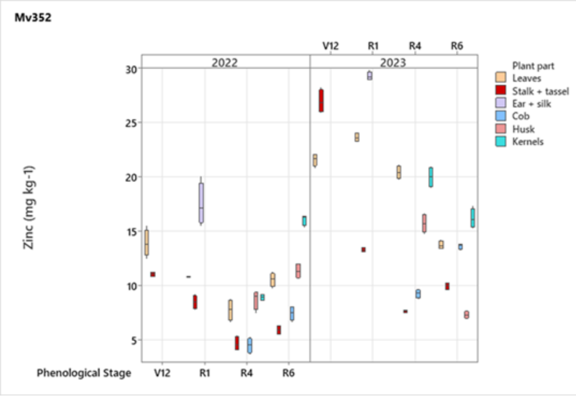


Appendix 4. Micronutrients uptake of maize as a function of phenological stages under irrigated and rain-fed conditions. **Fe:** Phenological Stage effect: ns | Hybrid: ns | Treatment: p<0.01 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001, Treatment*Plant Part: p<0.01. **Mn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Treatment: p<0.05 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage, Hybrid*Plant Part: p<0.001. **B:** Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.01 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage: p<0.05. **Cu:** Phenological Stage effect: p<0.001 | Hybrid: ns | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: Hybrid*Phenological Stage, Hybrid*Plant Part, Treatment*Phenological Stage and Treatment*Hybrid*Phenological Stage: p<0.001, Treatment*Plant Part and Treatment*Hybrid*Plant Part: p<0.01. **Zn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Treatment: p<0.001 | Plant Part: p<0.001 | Interactions: ns. (Debrecen, 2023).



Appendix 5. Micronutrients uptake of maize as a function of phenological stages under irrigated conditions. **Fe:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage and Year*Plant Part: p<0.001, Year*Hybrid*Phenological Stage: p<0.01. **Mn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Year: p<0.01 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001. **B:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage and Year*Plant Part: p<0.001. **Cu:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Plant Part and Hybrid*Plant Part: p<0.001. **Zn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Plant Part, Hybrid*Plant Part and Hybrid*Phenological Stage: p<0.001. (Debrecen, 2022-2023).


Fornad
Iron (mg kg-1)
Mv352
Iron (mg kg-1)
Fornad
Manganese (mg kg-1)
Mv352
Manganese (mg kg-1)
Fornad
Boron (mg kg-1)
Mv352
Boron (mg kg-1)
Fornad
Copper (mg kg-1)
Mv352
Copper (mg kg-1)
Fornad
Zinc (mg kg-1)
2022
2023
V12
R1
R4
R6
Phenological Stage
Plant part
Leaves
Stalk + tassel
Ear + silk
Cob
Husk
Kernels



Appendix 6. Micronutrients uptake of maize as a function of phenological stages under irrigated conditions. **Fe:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage and Year*Plant Part: p<0.001, Year*Hybrid*Phenological Stage: p<0.01. **Mn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.05 | Year: p<0.01 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Hybrid*Phenological Stage and Hybrid*Plant Part: p<0.001. **B:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: ns | Plant Part: p<0.001 | Interactions: Year*Phenological Stage and Year*Plant Part: p<0.001. **Cu:** Phenological Stage effect: p<0.001 | Hybrid: ns | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Plant Part and Hybrid*Plant Part: p<0.001. **Zn:** Phenological Stage effect: p<0.001 | Hybrid: p<0.001 | Year: p<0.001 | Plant Part: p<0.001 | Interactions: Year*Phenological Stage, Year*Plant Part, Hybrid*Plant Part and Hybrid*Phenological Stage: p<0.001. (Debrecen, 2022-2023).