

Theses of Doctoral (PhD) Dissertation

**EVALUATION OF YIELD AND QUALITY OF MAIZE
(ZEA MAYS L.) HYBRIDS OF DIFFERENT GENOTYPES**

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1. Introduction

Maize (*Zea mays* L.), also referred to as corn, is one of the foundational cereal grains of civilization around the world and is currently widely produced globally, with over 1.24 billion tonnes grown on 200 million hectares of land (Erenstein et al., 2022), surpassing wheat and rice (Faostat, 2025). Grown on every continent except Antarctica (Orhun et al., 2013), maize has an average yield of 5640 kg ha⁻¹ (Zhang et al., 2023), reflecting advancements in breeding, agronomic practices, and technology. As a C4 plant, maize exhibits a special morphological feature called Kranz anatomy, which makes the crop well-suited to hot and dry climates (Sedelnikova et al., 2018), and earning the title 'queen of cereals' due to its highest yield potential (Thakur et al., 2020). Maize is essential not only for food security but also for livestock feed, industrial processing, and bio-based products. 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. Materials and Methods

2.1. Experimental site

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). The experimental setup was conducted on chernozem soil, having a 2.25 m/m% of humus content, 5.59 of pH, and 38.47 KA of Arany's Plasticity Index. According to the collected meteorological data, the year 2022 marked drought conditions. 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 56.6mm, leading to a severe drought stress. Consequently, these environmental conditions hindered optimal maize growth. A marked shift in climatic patterns occurred in September, bringing heavy rainfall totalling 152mm, which subsequently delayed the harvest until October. Conversely, 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, precipitation was average. However, half of the precipitation fell during May and July. Despite this, no substantial water stress has been observed that could be due to preserved water in the deeper soil layers and the optimal temperature conditions.

2.2. Experimental design and treatment

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 under irrigated conditions. Each plot was divided into three rows where the control and the spray-treated plots were separated by an empty row. 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. On 26th April, they were sown at an inter-row distance of 15.6 cm, establishing a population density of 62 000 plants/ha. 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, the seeds were sown in each row with the plantings spaced 15.6 cm apart

and a population of 65 000 plants/ha. The emergence of the hybrids took place 13 days post-sowing (3rd of May), and they were harvested on 28th September.

In 2022, a precision irrigation setup was incorporated into the experimental design, beginning on May 27 and lasting until August, providing 456.8 mm of irrigation water during the growing season (28 total applications). In 2023, in the plot that received water supply, irrigation began on June 18th and continued until August 10th, providing 374 mm of irrigation water during the growing season (12 applications in total).

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 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).

2.3.Data collection and statistical analysis

The measurements of dry matter were undertaken based on the classification system of phenological stages proposed by Hanway (Hanway, 1963). 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.

In addition, in 2022, 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 were recorded. 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 assess the photosynthetic activity with the Green Seeker Handheld meter

serving as the measurement instrument. Relative chlorophyll content was assessed 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 measurements, 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. 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.

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%.

The 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 p<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.

3. Results

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). While, in 2023, 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. Over the two years, 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).

ANOVA results of the cropping season of 2022 revealed that phenological stage and plant parts significantly influenced nitrogen, phosphorus and potassium contents, with hybrids effect notable for N and moderately for K, as Mv 352 accumulated slightly more nitrogen and potassium than Fornad. Significant interactions were found for Hybrid*Plant Part (N and P), and Hybrid*Phenological Stage for phosphorus. Maize accumulated most N, P and K during early growth, especially at V12, with Fornad Mv 352 absorbing up to 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, respectively (Figure 1, 2 and 3). K demand was especially high, particularly in stalks, which required more K than N. By silking, Mv 352 had absorbed 64.2% N, 87.8% P and 79.16% K, while Fornad absorbed 50.6% N, 55.7% P and 68.4% K. As maize transitions to the reproductive stages, nutrient allocation shifts to the ears and kernels development. At R6, kernels N accumulation were peaked at 138.19 kg ha⁻¹ (60.7%) for Mv 352 and 112.10 kg ha⁻¹ (61%) for Fornad. This was followed by accumulation in the stalk at 39.05 kg ha⁻¹ for Mv352 and 33.86 kg ha⁻¹ for Fornad. Moreover, P accumulations in the kernels peaked 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. K behaved differently as K uptake and accumulation peaked at R4 for Mv 352 achieving 100% of the total K and at R6 for Fornad, and was mostly retained by vegetative organs. Only 13.12% for Mv 352 and 17.3% for Fornad of the total K was

remobilized to kernels by maturity phase, indicating that grain-filling is not critical phase for K supply. Stalks were the primary source of K storage and partial remobilization, while N and P were more effectively redistributed to support kernel development.

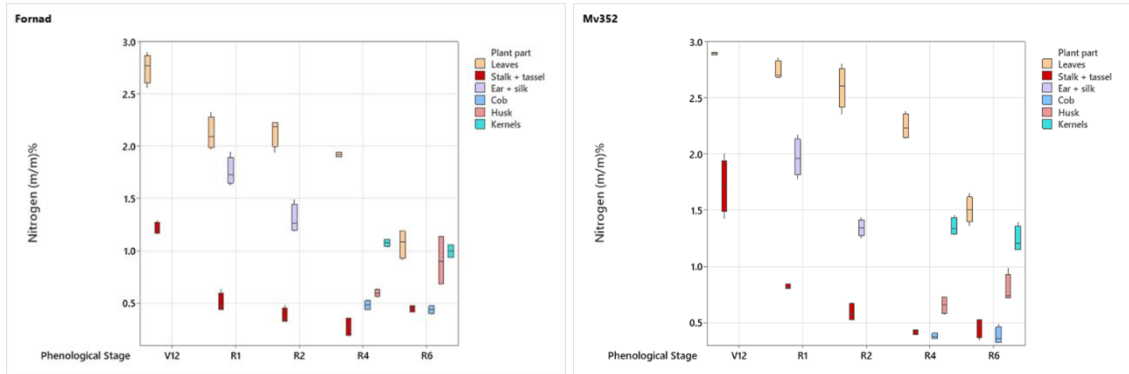


Figure 1. Nitrogen accumulation within maize hybrids as a function of phenological stages, 2022.

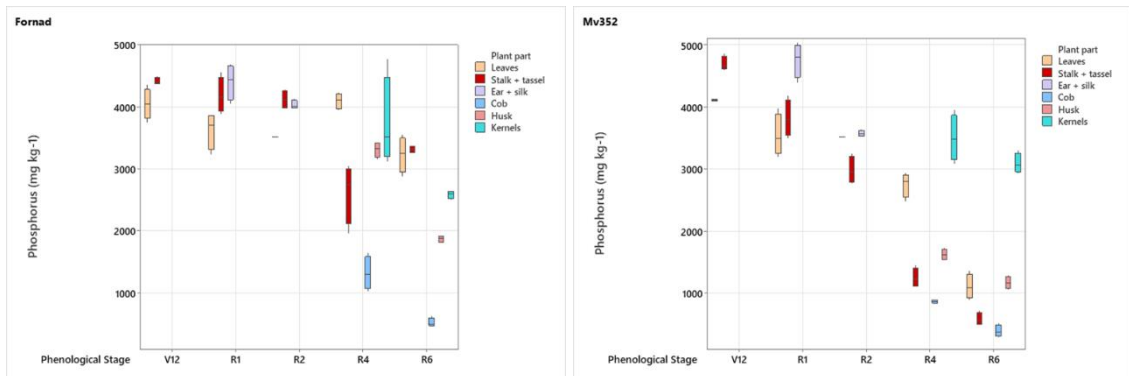


Figure 2. Phosphorus accumulation within maize hybrids as a function of phenological stages, 2022.

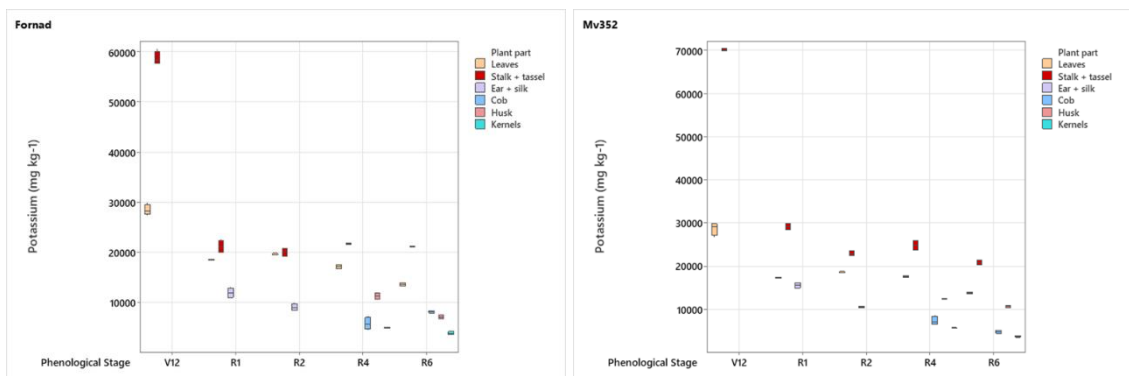


Figure 3. Potassium accumulation within maize hybrids as a function of phenological stages, 2022.

In 2023, however, the accumulation of nitrogen was significantly affected by treatment, phenological stage, plant part, and hybrid as well as the interaction of Hybrid*Plant Part. Mv 352 under irrigation retained the most N content (Figure 4). Throughout the plant growth and development, N was mainly stored in leaves until R4, then shifted to kernels.

At V12, under irrigation, Mv 352 and Fornad absorbed 26.8% and 39.2% of the total N content, respectively. While, under non-irrigated conditions, their accumulations were 34.3% and 36.2%, respectively. By the time of silking, N uptake reached 54.1% in Mv 352 and 78.1% in Fornad under irrigation, 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. In contrast, the maximum N accumulation occurred at R6 for Mv352 under irrigated conditions and for both hybrids under non-irrigated conditions. At maturity stage, the maximum N accumulations in the kernels was 174.47 kg ha⁻¹ and 151.01 kg ha⁻¹ (equal to 63.4% and 68.5%) for Mv352 under irrigated and non-irrigated conditions and 104.41 kg ha⁻¹ and 120.25 kg ha⁻¹ (equal to 63.6% and 68.6%) for Fornad under irrigated and non-irrigated conditions.

Phosphorus accumulation was also significantly influenced by treatment, phenological stage, plant part and Treatment*Phenological Stage interactions. Irrigated plants accumulated more P content. At V12, P uptake reached 33.4% and 29.7% in Mv 352 and Fornad, respectively, under irrigated conditions, and 43.3% and 22.7%, respectively, under non-irrigated conditions (Figure 5). By the time of silking, Mv352 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. 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.

Potassium uptake was significantly influenced by (p<0.05), phenological stage and plant part (p<0.001). K 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 6). Interestingly, maize had achieved its maximum K accumulation at the silking stage in Mv352 (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. Throughout the growing season, the stalk was the main K reservoir. At R6, Mv 352 accumulated a total of 315.5 kg ha⁻¹ under irrigation and 203.59 kg ha⁻¹ without irrigation. Fornad, however, accumulated 148.89 kg ha⁻¹ under irrigation and 176.04 kg ha⁻¹ without irrigation. However, only

10-16% of total K was remobilized to kernels, highlighting lower translocation efficiency compared to nitrogen and phosphorus.

Overall, when comparing the accumulation of nutrient between the two cropping seasons, 2023 accumulated significantly more nitrogen and potassium than in 2022, unlike phosphorus accumulation peaked in 2022 especially for Fornad.

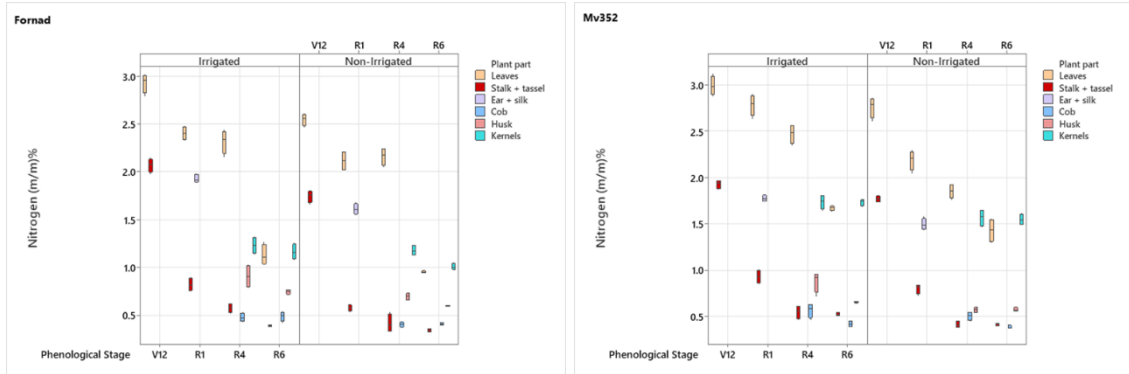


Figure 4. Nitrogen accumulation within maize hybrids as a function of phenological stages under irrigated and rainfed conditions, 2023.

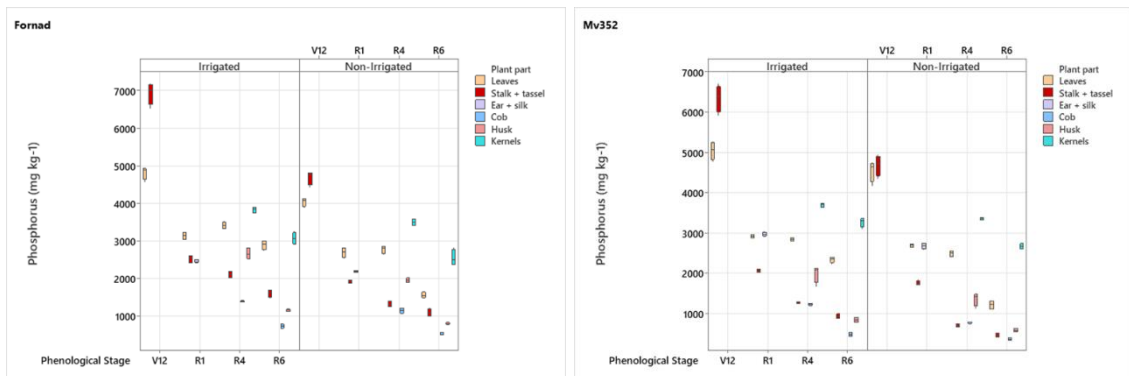


Figure 5. Phosphorus accumulation within maize hybrids as a function of phenological stages under irrigated and rainfed conditions, 2023.

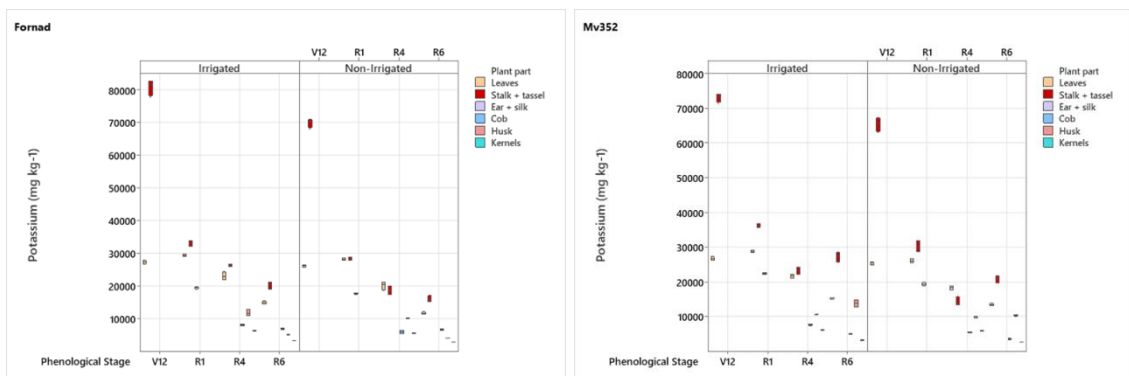


Figure 6. Potassium accumulation within maize hybrids as a function of phenological stages under irrigated and rainfed conditions, 2023.

It was found based on the correlation analysis of the cropping season of 2022, Fornad yield was strongly linked to nitrogen uptake, indicating that N availability was critical for grain formation (Table 1). In contrast, Mv 352 yield correlated positively with multiple

nutrients (N, P, K, B, Ca, Cu, Fe, Mg, Mn, S), indicating a broader nutrient dependency. Zinc showed a negative correlation with Mv 352 yield. Whereas, in 2023, under irrigation, Fornad's yield strongly correlated with Mg and moderately with K, B, P and S, but negatively with Cu, Zn and Fe (Table 2). Mv 352, however, showed strong positive links to N, P, K, Mg and S, with minor or negative ties to micronutrients. Without irrigation conditions, Fornad relied on N, P and to some extent to K and Mg, while B, Ca, and S and most micronutrients were negatively associated (Table 3). Mv 352, however, showed positive correlations with Fe, Mn, Cu, and Zn and weaker or negative ones with other nutrients. Over the two years, under irrigation conditions, Fornad's yield was strongly linked to P, K, B, Fe, S and Zn, and moderately to N, but negatively to Ca, Cu, Mg and Mn. While, Mv 352's yield was strongly associated with N, P, K, and B, and moderately with Ca, Cu, Mg and Zn with small positive correlations with S and negative one with Fe.

Table 1. Correlations between maize yields and nutrient uptake under irrigated conditions, 2022. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

	Fornad	Mv 352
Nitrogen	0.64	0.73
Phosphorus	-0.55	0.95
Potassium	-0.7	0.91
Boron	-0.58	0.8
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

Table 2. Correlations between maize yields and nutrient uptake under irrigated and non-irrigated conditions, 2023. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

	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

Table 3. Correlations between maize yields and nutrient uptake under irrigated conditions, 2022-2023. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

	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

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 Mv 352 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 (Figure 7). In 2023, water regime increased Mv 352's oil and protein content by 5.7% and 4.8%, respectively. While foliar fertilization increased Fornad's oil and protein content by 18.3% and 29.8%, respectively. Starch content was higher in Fornad, regardless of irrigation or foliar application. Over the two years, grain moisture was mainly controlled by hybrid and treatment, with higher moisture in Mv 352 showing slowed drying (Figure 8). 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.

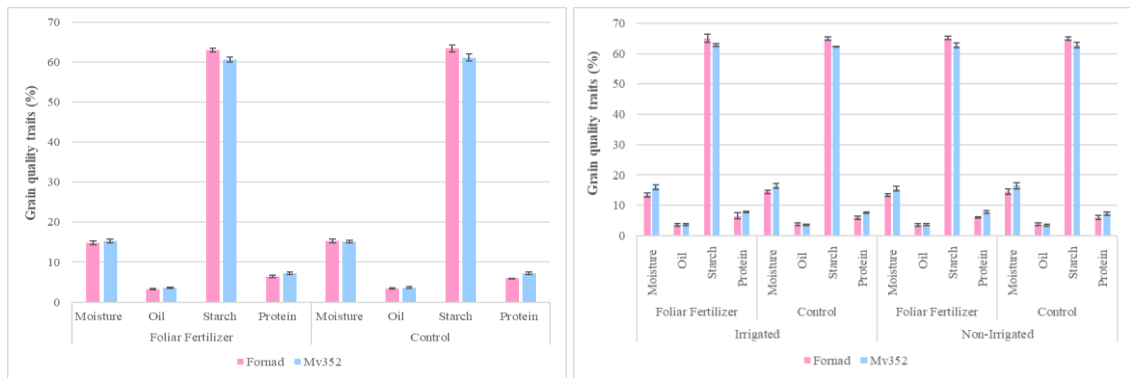


Figure 7. Grain quality traits of maize, in 2022 (left) and 2023 (right). Statistical significance was assessed using Tukey’s test at ($p < 0.05$).

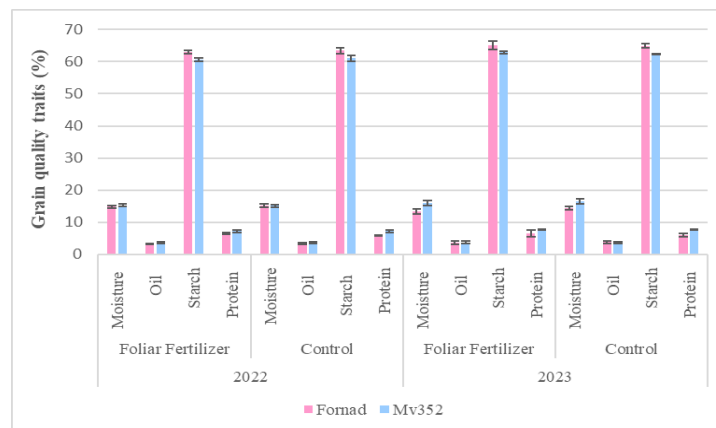


Figure 8. Grain quality traits of maize, 2022-2023. Statistical significance was assessed using Tukey’s test at ($p < 0.05$).

Grain yield was influenced by hybrid, water regime and foliar fertilization. In 2022, Mv 352 yielded $13,273 \text{ t ha}^{-1}$, 312 kg less than Fornad (Figure 9). 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% ($13.59 \text{ vs. } 12.48 \text{ t ha}^{-1}$). 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 (Figure 10). 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.

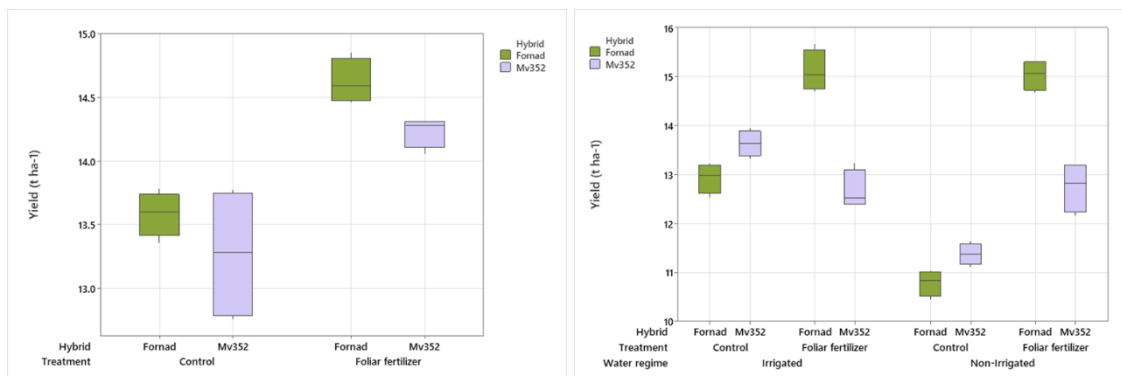


Figure 9. Grain yield of maize in response to foliar fertilization, under irrigation in 2022 (left) and under two water regimes in 2023 (right).

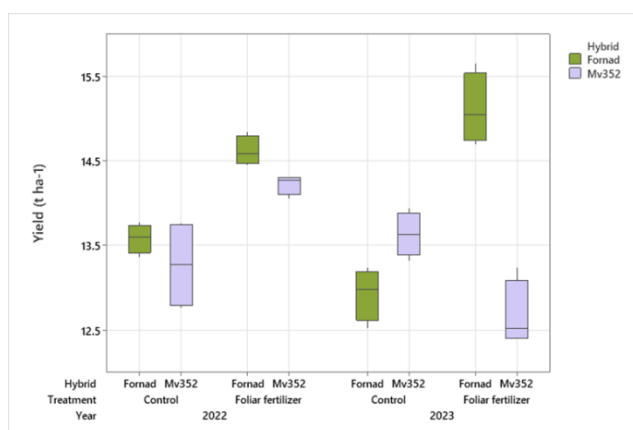


Figure 10. Maize yield response to foliar fertilization under irrigated conditions, 2022-2023.

The correlation analysis between yield and quality traits revealed that in the cropping season of 2022, Fornad's yield was strongly correlated to protein content, negatively with oil content and exhibited a weak negative trend with starch and moisture contents (Table 4). While Mv 352 showed a slight positive correlations between yield and oil content, a greater correlation with moisture content, and a weak correlation with protein.

In 2023, under irrigation, Fornad yield was moderately linked protein content, slightly to starch content and negatively to moisture and oil contents (Table 5). While Mv 352, showed a strong positive correlation with moisture content and negative correlations with oil, protein, and starch contents. In contrast, under non-irrigated conditions, Fornad's yield was strongly negatively correlated with moisture, moderately negatively correlated with protein, and slightly negatively correlated with oil (Table 5). Mv 352's yield however, demonstrated moderate positive correlations with protein and oil contents, as well as slight negative correlations with moisture and starch contents.

Over the two-year period, Fornad's yield correlated positively with protein content and a slightly with starch content, but negatively with oil and moisture contents

(Table 6). In contrast, the Mv 352 showed negative correlations with starch, protein and oil content, and a minimal or even negligible correlation with moisture content.

Table 4. Correlations between maize yield and grain quality traits, 2022. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

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

Table 5. Correlations between maize yield and grain quality traits under irrigated and non-irrigated conditions, 2023. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

	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

Table 6. Correlations between maize yield and grain quality traits under irrigated conditions, 2022-2023. Values represent Pearson correlation coefficients (r). Significant correlations were defined as $p < 0.05$.

	Moisture	Oil	Protein	Starch
Fornad 2022-2023	-0.39	-0.66	0.49	0.03
Mv 352 2022-2023	0.01	-0.24	-0.38	-0.70

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.

4. New scientific results

1. Dynamics of dry matter and nutrient accumulation:

- 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. Whereas, 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 nutrition, 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.

5. Practical use of the 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.

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7. Publications



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Candidate: Ibtissem Balaout
Doctoral School: Kálmán Kerpely Doctoral School
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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.
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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





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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.

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