

Theses for doctoral dissertation (PhD)

**IMPACT OF PRECISION NUTRIENT AND WATER SUPPLY OF
MAIZE ON CERTAIN PHYSIOLOGICAL PROCESSES**

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1. INTRODUCTION

“To watch the corn grow, or the blossoms set; to draw hard breath over the plough or spade; to read, to think, to love, to pray are the things that make men happy.”

John Ruskin

Nowadays, population growth and climate change pose new challenges for agricultural production. The world population is 7.8 billion (CSO, 2020) and is on an upward trend, expected to reach 9.2 billion by 2050. Meat production is projected to increase to 455 million tonnes, which will require much more cereal production, while arable land can only be increased in some regions and drinking water supplies are declining. Due to pandemic COVID-19, the number of hungry people increased significantly from 8.4% to 10.4% in 2020 (FAO, 2021). To meet increased food demand, agricultural production efficiency will need to be improved. Crop production, including maize, is of particular importance.

Maize is one of the *world's* most important and most abundant crops, accounting for 13% of the world's land used for crop production in 2018. This represents an increase of 46.2% compared to the average in the 1990s (Nagy, 2020). The USA is the largest maize producing country, with 564.93 million tonnes produced in 2019 and an average yield of 7.89 t/ha, followed by China (260.96 million tonnes; 6.31 t/ha) and Brazil (101.14 million tonnes; 5.77 t/ha) (FAO, 2019). Argentina and Ukraine also produce significant quantities. Total production in the *European Union* was 70.09 million tonnes, with an average yield of 7.86 t/ha. The largest maize producing countries are Romania (9th in the world's top 10, 17.432 million tonnes), France (12.85 million tonnes), Hungary (8.23 million tonnes), Italy (6.28 million tonnes), Spain (4.18 million tonnes) in order (FAO, 2021)

In Hungary, maize occupies the largest share of the area sown. It covers an area of 1,028,000 hectares, with an average yield of 8.06 t/ha (KSH, 2019). The area under production varied between 955 (2018) and 1287 (2001) thousand hectares. Yield averages show a wide variation, with the lowest in 1993 (3.5 t/ha) and the highest in 2016 (8.63 t/ha).

Yield variability is strongly influenced by the weather, but with the proper cultivation practices, the extreme adverse effects of weather can be mitigated. The right choice of hybrids plays a key role in this, with a significant impact on yield and quality (Izsáki, 2006; Győri, 2010; Pepó, 2017). Nutrient replenishment, including fertilisation, is a key technological element. Nitrogen (N) fertilisation is of particular importance as it largely determines yield and quality (Győrffy et al., 1965; Láng, 1973; Nagy, 2007), but the amount applied and the timing of its application

are of great importance (Berzsenyi and Lap, 2003; Nagy, 2017; Széles et al., 2021), thus avoiding excessive N application and environmental pollution.

Maize is a versatile feed, energy source and industrial raw material. Maize can be used to produce nearly four thousand products (Nagy, 2020). It is an important bulk feed and seed, and also plays a prominent role in starch, sugar and alcohol production (Gyóri, 2002). It has many uses as a whole plant, as a biogas feedstock, green manure and animal bedding (Zavatto et al., 2007). It plays an essential role in the food supply of the population (Bocchi and Castrignanò, 2007; Confalonieri et al., 2011; Torriani et al., 2007). In terms of global use, 13% was used as food in 2020 (OECD-FAO, 2018). In our country, 4.3-4.5 million tonnes have been used, of which 2 million tonnes are used for feed and industrial purposes. Seed demand is estimated at 30-40 thousand tonnes (KSH, 2020).

Objectives of the research

Nitrogen (N) is one of the most important factors determining yield and quality, so determining the exact amount, distribution and timing of application according to crop needs is very important to avoid yield variations from year to year and to avoid environmental pollution. This requires the site-specific use of precision tools that provide up-to-date information on the condition of the crop.

The aim of my research

- To investigate and quantify the effects of fertilisation (basal and top dressing) and irrigation on chlorophyll content, yield and nutritional values (starch, protein and oil content) of maize hybrids of different genotypes.
- Predicting the onset of water stress using stomatal conductance studies.
- To show how the negative impact of weather factors can be mitigated by analysing the combined effect of the crop year and agrotechnical factors (fertilisation, irrigation, genotype).

2. MATERIAL AND METHODS

2.1 Site description

2.1.1 Location of the site, experiment setup and layout

Studies were carried out at the University of Debrecen Látókép Experimental Station (47° 33' N, 21° 26' E, 111 m) on a deep humus layer, medium plasticity lowland calcareous chernozem soil, under irrigated and non-irrigated conditions between 2018 and 2020. The experiment was a two replicate (1.5 ha) field trial in a split-split-plot design.

2.1.2. Soil conditions of the site

Based on the results of the soil analysis, the soil of the experiment has the following characteristics: pH_{KCl} is 6.6, slightly acidic, which is optimal for the nutrient uptake of the plants. In the upper layer (20 cm) of the soil, the Arany's plasticity index is 39. In the upper layer (20 cm), the organic matter content is 2.3 %, while in the 120 cm layer it is less than 1.0 %. The soil is well supplied with potassium and medium with P. The soil is well supplied with potassium and medium with P. The soil is well supplied with potassium and medium with P.

2.1.3. Weather conditions in the production area

In 2018, the total rainfall for the growing crop year was 319 mm, 27 mm below the multi-year average (346 mm), but the temperature was 2.1° C, warmer than the average (17.5° C). In 2019, the growing crop year received only 290 mm of rainfall, 56 mm below the multi-year average, and the temperature was 0.9° C warmer. The 2020 growing crop year saw a significant rainfall of 449 mm, 103 mm above the multi-year average, with temperatures only 0.2° C warmer.

2.1.4. Treatments of the experiment

In the experiment, N fertiliser was applied as basal and top dressing in a split application with no fertiliser (control) treatment (Table 1). The spring application of 60 and 120 kg N/ha as base fertiliser was followed by two top dressings at V6 and V12 phenophases at +30 and +30 kg N/ha. The agrotechnical interventions applied are shown in Table 2. The previous crop was maize in all years. Five hybrids of different genotypes were used in the experiment under irrigated and non-irrigated conditions. In the present study, the hybrids Sushi (FAO 340),

Fornad (FAO 420) and Armagnac (FAO 490) were analysed under irrigated and non-irrigated conditions.

2.2. Measuring instruments and test methods

The portable handheld Field Scout TDR 300 probe was used to determine soil moisture. Relative chlorophyll content was determined using a MINOLTA SPAD-502 chlorophyll meter. Leaf stomatal conductance was determined using the Sc-1 Leaf Porometer. Post-harvest content (starch, protein and oil) was determined using a Foss- Infratec 1241 Grain analyzer from 0.5 kg dmmples of maize grain taken at harvest. Statistical evaluation was performed using the statistical software package SPSS. 14.0 for Windows.

3. RESULTS

3.1. Effects of N fertiliser applied at different times and rates, growth stages, genotype, irrigation and crop year on the relative chlorophyll content of maize

The ANOVA results averaged over three years *for non-irrigated and irrigated variants* showed that the main factors (fertilisation, phenophase hybrid and crop year) were strongly ($p < 0.001$) related to the evolution of SPAD. On average over the three years studied, the highest verifiable SPAD value for maize in the *non-irrigated version* was obtained with the 120 kg N/ha base + 30 kg N/ha top dressing (V6₁₅₀) (51.2), which represents an increase of 18.2% from the lowest SPAD value (43.3) in the A₀ treatment. *In the irrigated variant*, the V12₁₈₀ treatment (50.8) provided the statistically proven highest SPAD value, which is 16.2% higher than the *non-irrigated* SPAD value (43.7). *In the non-irrigated variant*, the effective fertiliser treatment varied from year to year. In 2018, the V6₉₀ treatment (51.2) was effective, while in 2020, the V6₁₅₀ treatment (50.2) was effective. *In the irrigated variant*, the V6₉₀ treatment (48.7) had the highest significant value (51.2) in 2018, while in 2020 the highest significant value was obtained with the largest top dressing treatment (V12₁₈₀). Among maize hybrids in the non-irrigated variant, a significant difference was observed in 2020, where the highest SPAD value was obtained by the hybrid Fornad (49.3), ahead of Armagnac (5.6%) and Sushi (4.0%). No significant difference was found between the hybrids in the *irrigated varieties* in any year. The SPAD value of maize hybrids was differently modified by the crop year. In the non-irrigated variant, there was an increase in all three hybrids in 2019 compared to 2018. In the irrigated variant, the crop year effect on the average of treatments was least for Sushi and most for the longer maturity hybrid Armagnac. SPAD increased with the growth of maize plants. The lowest value *in the non-irrigated version* was in the V6 stage (41.3), which increased by 28.8% for the R1 stage (53.2). The highest crop year effect was observed in the V6 phenophase between 2020 and 2018 (11.3%). Also *in the irrigated version*, the lowest SPAD value was observed in the V6 stage (40.8) and the highest in the R1 (52.7) phenophase, with an increase of 29.2%. The highest crop year effect was observed in V12 stage, between 2019 (49.9) and 2020 (43.3).

In both irrigated variants, top dressing treatments significantly influenced the SPAD of the hybrids. The highest SPAD value was detected in V6 (44.6; 2020) and V12 phenophases (55.3; 2018) in the Sushi hybrid, while in R1 stage it was detected in the Fornad hybrid (61.0; 2019). Evaluating *the irrigation effect*, averaged over the treatments, it can be concluded that the SPAD value was not statistically proven to be higher in the irrigated treatment than in the

natural rainfall treatment. A reduction in SPAD was observed in all three years under irrigation, with the reduction being verified in 2020 in the 60 kg N/ha (A_{60}) and $V12_{120}$ treatments applied as basal fertiliser ($p < 0.05$). When examined by phenophase, in 2020, a reduction in SPAD was verified in the V6 and V12 growth stages ($p < 0.05$).

3.2. Effects of N fertiliser applied at different times and rates on stomatal conductance of maize hybrids in non-irrigated treatments

Stomatal conductance showed a decreasing trend with the progression of phenological stages in both years, with decreases of 43.9% and 32.1% ($p < 0.001$; $p < 0.01$) for the R1 stage. Application of higher N fertiliser increased stomatal conductance, with the exception of the R1 phenological stage, which showed a decrease compared to the A_0 treatment. In 2019, the decrease was caused by a decrease in soil moisture. In 2020, although sufficient water was extracted from the soil, the periodic water deficit due to the large leaf area and rapid transpiration of the plant caused stomatal closure. The stomatal conductance of the plants ranged widely between V6 and R1 phenophases. The lower value of the interval was 208 and the upper value $589 \text{ mmol m}^{-2} \text{ s}^{-1}$. The most suitable environmental conditions for the plants were provided by the non-fertilised ($589 \text{ mmol m}^{-2} \text{ s}^{-1}$) treatment in 2019 and the $V6_{150}$ ($476 \text{ mmol m}^{-2} \text{ s}^{-1}$) treatment in 2020 (Figures 1 and 2).

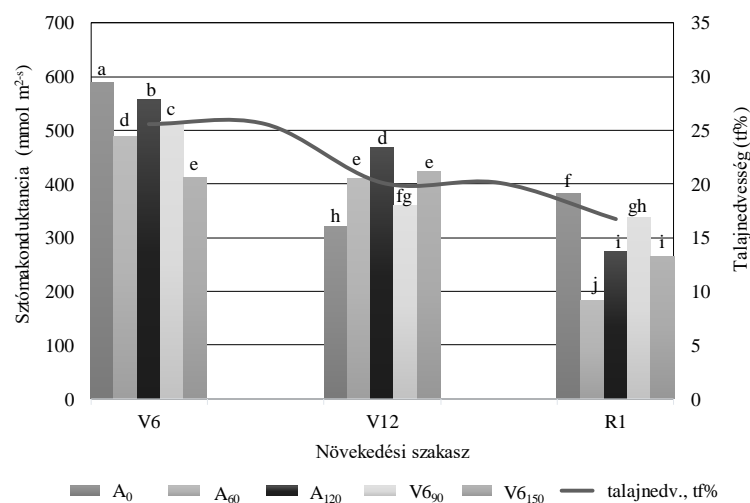


Figure 1: Trends in stomatal conductance and soil moisture by growth stage (Debrecen, 2019)

Note: The different lower case letters indicate the difference between fertiliser treatments based on Duncan's test ($p < 0.05$).

Our results confirm the finding of Han et al. (2006) that increasing N fertiliser application can modify leaf stomatal conductance, thereby enhancing adaptability.

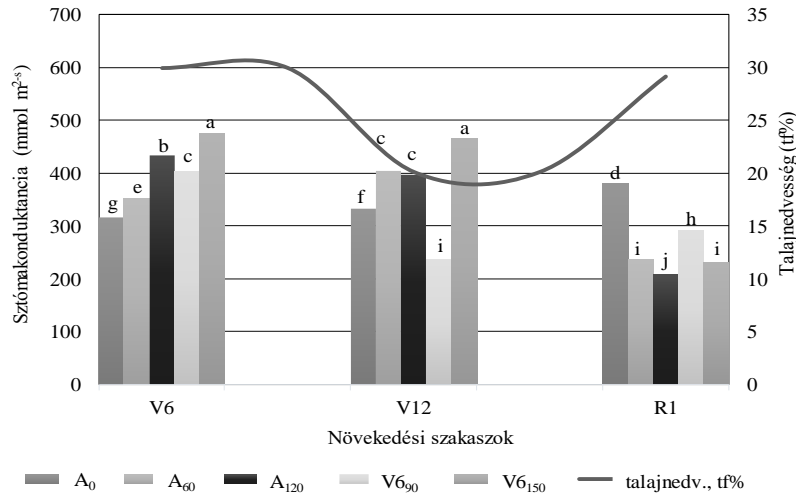


Figure 2: Trends in stomatal conductance and soil moisture by growth stage, (Debrecen, 2020)

Note: The different lower case letters indicate the difference between fertiliser treatments based on Duncan's test ($p < 0.05$).

Our results, averaged over the treatments, are in agreement with the finding of Kron et al. (2008) that, as the phenological stages progress, the stomata of plants become increasingly closed, with a decrease in stomatal conductance. The lowest value was reached during the R1 phenophase in both years.

3.3. Effect of N fertiliser applied at different times and rates, genotype, irrigation and crop year on maize yield

Maize hybrids yield. Averaged over three years, fertiliser application had the largest significant effect of the main factors in the *non-irrigated variant*. Hybrid traits significantly determined yield, while the effect of crop year was not significant. The pooled analysis of variance by year showed that fertilisation affected yield in all three years, hybrid traits in 2019 and 2020 ($p < 0.001$). Averaged over the three examined years, the lowest yield (7.28 t/ha) in the *non-irrigated variant* was observed in the non-irrigated treatment (A₀). The treatment A₁₂₀ (13.18 t/ha; $p < 0.05$) had the highest yield increasing effect. *In the irrigated version*, compared to the treatment A₀ (7.44 t/ha), the basal treatment of 120 kg N/ha (A₁₂₀) resulted in a yield increase

of 2.60 t/ha (82%; $p < 0.05$). *Under irrigated conditions*, the irrigated version provided higher yields in all fertiliser treatments. The yield increasing effect of irrigation among the treatments was verified in the V6₉₀ treatment ($p < 0.05$), which was 1.61 t/ha.

The analysis by year showed that in *all three years*, the non-irrigated version had the lowest yield in the *no fertiliser* (A₀) treatment and the maximum ($p < 0.05$) yield in the higher basal fertiliser (A₁₂₀) treatment. The *effect of irrigation* was verified in 2019, in the V6₉₀ treatment ($p < 0.05$), which was 1.51 t/ha. Maize yield was *the highest in 2019* among the years studied in both irrigation variants. Looking at the maize hybrids, averaged over the treatments, it was found that the hybrid Fornad achieved the highest yield (10.81 t/ha) *in the non-irrigated variant*. *In the irrigated variant*, the highest yield (11.16 t/ha) was obtained with the Armagnac hybrid. Irrigation affected the yield of the Armagnac and Sishi hybrids by 0.1% and of the Fornad hybrid by 5%. The response of maize hybrids to fertiliser was investigated as an average over three years. *In the non-irrigated variant*, the treatment A₁₂₀ (13.76 t/ha) had a reliable effect on yield growth in the Armagnac (13.76 t/ha) and Fornad (13.50 t/ha) hybrids, while the treatment V6₁₅₀ (12.28 t/ha) had a reliable effect on the Sushi hybrid. *In the irrigated version*, treatment A₁₂₀ provided significant yield maximum in all three hybrids. The top dressing treatments had a significant yield increasing effect in 2018 for all three hybrids and in 2020 for hybrid Sushi. *In the irrigated version*, Fornad and Sushi hybrids had a significant yield enhancing effect of treatment A₁₂₀ in two years (2019, 2020). The reliable *irrigation effect* was observed in 2018 for the V6₉₀ treatment, Armagnac (3.5 t/ha), Fornad (2.36 t/ha) and hybrid Sushi (1.92 t/ha), and in 2019 for the V12₁₈₀ treatment for hybrid Sushi (2.12 t/ha) ($p < 0.005$).

3.3 Effects of N fertiliser applied at different times and rates, genotype, irrigation and crop year on maize quality

3.3.1 Effect of N fertiliser, genotype and crop year applied at different times and rates on the protein content of maize in non-irrigated and irrigated treatments

A four-factor analysis of variance (year, fertiliser, hybrid and irrigation) showed that the main factors, except irrigation, influenced the protein content by 0.1% on average over three years. There was minimal difference in protein content between the non-irrigated (8.05 g/100 g dm) and irrigated (7.96 g/100 g dm) maize varieties averaged over three years. The protein content of maize was significantly affected by V6₉₀ (8.61 g/100 g dm) in the non-irrigated and A₁₂₀ (8.46 g/100 g dm) in the irrigated maize. Compared to the treatment A₀, the protein content of

maize increased by 20.3% in the non-irrigated version and by 18.8% in the irrigated version. The modifying effect of irrigation on protein content could not be reliably demonstrated in any of the fertiliser treatments. Among the examined maize hybrids, *in the non-irrigated variant*, a reliable protein increasing effect of fertilisation was observed in the Sushi hybrid, treatment V6₁₅₀ (9.10 g/100 g a-1; p<0.05), which increased protein content by 28.3% compared to treatment A₀ (7.09 g/100 g a-1). *In the irrigated version, the highest* protein content was obtained with higher nutrient levels in the Armagnac (V6₁₅₀; 9.04 g/100g dm) and Fornad hybrids (V12₁₈₀ ; 8.48 g/100g dm) and lower in the Sushi hybrid (A₁₂₀; 8.72 g/100g dm). Changes in protein content *due to irrigation* were not statistically proven for any of the hybrids. The protein content of the hybrids was positively affected by top-dressing, with the exception of the hybrid Fornad 2020. In the irrigated version, the protein content of the Armagnac hybrid was effectively affected in two years (2018 and 2020) by the application of top dressing at a rate of 120 kg N/ha at the 6-leaf stage (V6₁₅₀). Regarding the effect of irrigation, it can be concluded that in all three years, the effect of irrigation on protein content reduction was more significant in all three hybrids in the top dressing treatments.

3.3.2 Effect of N fertiliser, genotype and crop year applied at different times and rates on starch content of maize in non-irrigated and irrigated treatments

Starch content of maize hybrids. The main factors (year, fertiliser, hybrid) influenced 0.1% of the starch content and the respective value of irrigation is 1%. There is no reliable difference between the starch content of the non-irrigated (75.18 g/100 g dm) and irrigated (75.42 g/100 g dm) varieties. The starch content per year showed that both the non-irrigated (78.29 g/100 g dm) and irrigated (78.66 g/100 g dm) varieties had the highest starch content in 2020.

In both the non-irrigated (A₀) and the irrigated treatments, the highest starch content was 75.54 g/100 g dm and 75.86 g/100 g dm, respectively. The starch content decreased with increasing N doses. The largest decrease was observed in both the non-irrigated (0.93 g/100 g dm) and irrigated (0.97 g/100 g dm) treatments in V6₁₅₀ compared to treatment A₀.

Among the tested hybrids, the hybrid Sushi had the lowest starch content in both the non-irrigated (73.96 g/100 g dm) and irrigated (74.47 g/100 g dm) treatments.

The fertiliser treatments showed a non-significant decrease in starch content of the hybrids in both the *non-irrigated and irrigated treatments* compared to the A₀ treatment.

The starch content of maize hybrids was influenced by the crop year. The highest increase in starch content was in the Sushi hybrid, 4.9% in the non-irrigated and 5.2% in the irrigated variant.

Differences in starch content *due to irrigation* in all three hybrids could not be statistically confirmed in any year.

3.3.3 Effect of N fertiliser, genotype and crop year applied at different times and rates on oil content in non-irrigated and irrigated treatments

Of the main factors, crop year affected the oil content in 0.1% and hybrid characteristics in 5%. The highest oil content was obtained with 60 kg N/ha of basal fertiliser in both the non-irrigated (4.66 g/100 g ha⁻¹) and irrigated (4.53 g/100 g ha⁻¹) treatments, which did not differ from the other treatments applied, as determined by the Duncan test. In all three years, the oil content was higher in the non-irrigated version, with the highest difference in 2019 (1.8%), where the effect of irrigation on the oil content was confirmed ($p < 0.01$). In the *non-irrigated variant*, the highest oil content was measured in the treatment A₁₂₀ (4.39 g/100g dm) for the hybrid Armagnac, the lowest in the treatments Fornad (4.83 g/100g dm) and Sushi (4.80 g/100g dm), and the highest in the treatment A₆₀.

In the *irrigated version*, the Armagnac hybrid was in treatment A₁₂₀ (4.39 g/100g dm), the Fornad hybrid in treatment A₀ (4.62 g/100g dm) and the Sushi hybrid in treatment A₆₀ (4.80 g/100g dm). The measured differences were not significant in any of the variants. Under irrigated conditions, a significant increase in oil content was observed in 2019 ($p < 0.01$), with 4.99 g/100g dm in the non-irrigated and 4.90 g/100g dm in the irrigated variant.

3.4 Results of the correlation analysis

The *correlation between fertilisation and SPAD value* showed that as the phenological stages progressed, the correlation between the two factors was also closer in both the non-irrigated and irrigated versions.

When examining the relationship between SPAD value and yield, the closest relationship in *non-irrigated variant* was at the V12 ($r=0.828^{***}$) and R1 ($r=0.868^{***}$) phenophases in 2020 for hybrid Fornad, in the *irrigated variant*, it was at the V12 ($r=0.856^{***}$) for Fornad and at the R1 stage ($r=0.865^{***}$) for the hybrid Sushi.

Based on the coefficient of determination value of the correlation between *stomatal conductance and soil moisture*, soil moisture determined stomatal conductance by 69% ($r^2 = 0.689$). In 2020, in the R1 growth stage, no significant relationship between the two factors was demonstrated.

The linear correlations *between stomatal conductance and yield* were dominated by nutrient-dependent correlations. In 2019, medium correlations ($r = -0.69^*$, $r = 0.72^*$, $r = -0.59$) were observed in V6, V12 and R1 growth stage. In 2020, the correlation between the two factors was close ($r = 0.87^*$, $r = -0.78^*$) in the V6 and R1 growth stages. No reliable correlation could be detected in the V12 phenophase.

The correlation between fertiliser application and maize hybrid yield was stronger in the irrigated variant ($r = 0.846^{***}$) than in the non-irrigated variant ($r = 0.778^{***}$), averaged over the three examined years. Based on the coefficient of determination value of the regression analysis, fertiliser application had the greatest effect on maize yield in 2020 (74%, $p < 0.001$) and 2018 (81%, $p < 0.001$) in the non-irrigated and irrigated variants, respectively. However, it had the least effect in both variants in 2019 (34% and 60%) ($p < 0.001$).

The correlation between fertilisation and protein content was weak in both the non-irrigated ($r = 0.505^{***}$) and irrigated ($r = 0.496^{***}$) versions averaged over the three years. The strongest correlation was in 2018 in the non-irrigated and in 2019 in the irrigated version.

The correlation between protein content and maize hybrid yield was stronger in the irrigated than in the non-irrigated variant averaged over the three years.

The relationship between fertiliser application and starch content was not significantly confirmed in any of the variants averaged over three years. The strongest correlation was found in both non-irrigated and irrigated variants in 2019 ($r = 0.664^{***}$; $r = 0.666^{***}$).

The correlation between fertilisation and oil content was not significantly confirmed in the non-irrigated and irrigated variants on average over three years.

Only in the irrigated variant, the *Armagnac hybrid* showed a significant relationship in 2019, showing a medium correlation ($r = 0.725^{***}$), with a coefficient of determination value of 53%.

4. CONCLUSIONS AND RECOMMENDATIONS

Successful maize production requires the application of adequate amounts of nutrients, taking into account the soil conditions and the needs of the crop. Our conclusions are based on 3 years of research. The results are based on control plots that have not been fertilised for several decades.

Looking at the SPAD value of maize, it can be observed that, averaged over three years, the V6₁₅₀ treatment provided the statistically proven highest value in the non-irrigated variant, while the V12₁₈₀ treatment provided the highest value in the irrigated variant. By year, in the 2018 average rainfall year, both variants were treated with top-dressing (V6₉₀) and in the 2019 dry year, no statistically significant difference was found. In the rainy year 2020, in the non-irrigated version, the treatment V6₁₅₀ was sufficient, whereas in the irrigated version, a higher N-dose (V12₁₈₀) was necessary to detect a reliable SPAD value.

Our research results support that irrigation reduces nitrogen concentrations in plants, which results in low chlorophyll concentrations in leaves. As vegetation progressed, SPAD increased. In our study, we found that top-dressing had a significant effect on SPAD in both irrigation regimes. Nagy, 2005; Pekurár, 2000; Csajbók and Kutassy, 2002; Ványiné, 2008.) Our studies showed that the relationship between SPAD value and crop size became stronger as the crop approached emergence.

Our stomatal conductance study showed that the stomatal conductance of plants decreased as the phenological stages progressed. Furthermore, we found that the application of N fertiliser can increase stomatal conductance and that soil moisture has an effect on the openness of plant stomata (Han et al. 2006).

When averaged over three years, non-irrigated and irrigated, the A120 base treatment had the greatest yield enhancing effect and was therefore the most effective treatment, confirming the results of Berényi et al. (2007). However, the basic treatment above 120 kg N/ha no longer increased yield, which is in agreement with the results of (Vad and Dóka, 2009; Dóka and Pepó, 2007; Ragán, 2017).

Maize yields were highest in the dry year 2019 in both irrigation variants of the examined years. In the non-irrigated version, the obtained yield was 11.26 t/ha, but it was not statistically different from the yields of the other two years. While in the irrigated version (11.86 t/ha), it was statistically higher than the average yields of 2018 and the rainfall-rich 2020.

Thus, our research results suggest that irrigation is more effective in a dry year than in a year with optimal water availability for maize. By examining the fertilizer response of hybrids, our

results partially supported the findings of (Muthukumar et al., 2007; Sitthaphanit et al., 2010; Ványiné & Nagy 2012; Széles et al., 2019) that head-dressing has a yield enhancing effect. Our results suggest that head manuring did not always have a yield enhancing effect, and thus its effectiveness depends largely on the effects of the main cropping factors. In our examinations, we found a stronger correlation between fertiliser application and yield in the irrigated version ($r=0.846^{***}$) than in the non-irrigated version ($r=0.778^{***}$).

Furthermore, in the non-irrigated variant, we confirmed the highest fertiliser use in the rainy crop year of 2020 (74%, $p<0.001$), and in the irrigated variant in the average crop year of 2018 (81%, $p<0.001$). Based on these results, it can be concluded that adequate water availability promotes N fertiliser uptake and utilisation by plants.

Our analyses on protein content showed that, with the exception of irrigation, the main factors affected the protein content of maize. In our research, we were able to demonstrate the effect of fertiliser application in increasing protein content in the non-irrigated and irrigated variants. This is in agreement with the results of several researchers (Pekáry, 1974; Győri, 2002; Loch and Nosticzius, 2004; Széles et al., 2018) that increasing N doses leads to an increase in the protein content of maize grain. With respect to the crop year, our results showed a significant increase in protein content of maize grain in the dry year 2019 and a decrease in the rainy year 2020. No effect was confirmed for the average crop year of 2018. The protein reduction effect of irrigation was significantly observed in the top dressing treatments.

The starch content of maize hybrids was affected by the main factors (year, fertiliser, hybrid) by 0.1% and by irrigation by 1%. There was no reliable difference between the starch content of the non-irrigated (75.18 g/100 g dm) and irrigated (75.42 g/100 g dm) varieties. High starch contents were measured due to the rainy year 2020. Based on our results, we found that the non-fertilised (A_0) treatment had the highest starch content in both varieties and that increasing the N doses decreased the starch content of the maize grain.

The highest reduction in starch content was observed in the V_{6150} treatment. Based on these results, it can be concluded that a rainy crop year has a positive effect on starch content, while a higher N dose has a negative effect. Among the main factors affecting the oil content of maize, the crop year had an effect of 0.1% and hybrid traits had an effect of 5%.

The highest oil content was obtained with 60 kg N/ha of basal fertiliser in both the non-irrigated (4.66 g/100 g ha^{-1}) and irrigated (4.53 g/100 g ha^{-1}) varieties.

The non-irrigated variant resulted in higher oil content in all three years. In the dry year 2019, the effect of irrigation on oil content was confirmed. The rainfall-rich year 2020 resulted in a decrease in oil content, the effect of which was statistically confirmed. Our study found that

irrigation and top dressing treatments decrease the oil content of maize grain. (Holou and Kindomhhou, 2011; Izsáki, 2014) in line with our results, we found that irrigation and head-dressing treatments reduce the oil content of maize grain.

5. NEW SCIENTIFIC RESULTS

1. It was confirmed that stomatal conductance decreased with plant development, but stomatal conductance could be increased by the application of N fertiliser. The highest yield is obtained when the average stomatal conductance is around $250 \text{ mmol m}^{-2} \text{ s}^{-1}$ during the growing crop year.
2. In the scope of the study, water deficit also occurred intermittently during the day, when due the higher LAI value, water transpiration is faster than water uptake. This might occur on days with evapotranspiration exceeding 5-6 mm/day, mainly in midday and early afternoon hours. In such cases, the soil around the root hairs of the plant dries out, water uptake ends and the stomata close. At this time, there is still sufficient water in the soil (2020, R1 phenophase), but it takes time for the water to flow. With these results, it has been demonstrated that by monitoring stomatal conductance before the onset of plant symptoms, drought-induced plant stress can be detected, thus preventing the onset of stress and avoiding yield loss.
3. In all three hybrids, Sushi (FAO 340), Fornad (FAO 420) and Armagnac (FAO 490), the effect of irrigation in reducing protein content was more significant in the top-dressing treatments in every examined year (2018, 2019, 2020). The largest reduction, in the average of hybrids, (0.45 g/100 g dm.) was observed in the V690 treatment compared to the A₀ treatment.
4. In the scope of the research it has been shown that the highest oil content (4.74 g/100 g dm.) was obtained in the early-maturity hybrid Sushi (FAO 340). The application of spring basal fertilizer was confirmed to increase the oil content ($p < 0.05$). In years with high precipitation, it may be necessary to apply higher N dose (top-dressing applied at 12-leaf stage) to increase the oil content of maize grain.

6. PRACTICAL USE OF THE RESULTS

1. The site-specific SPAD values provide an estimate of the N supply of maize hybrids, which forms the basis for planning the optimal N application in terms of quantity and timing. Based on this information, the expected yield can be estimated.
2. By measuring stomatal conductance, the physical changes in maize and the reduction in water available to plants can be monitored, i.e. water stress can be detected before symptoms appear. It helps to determine the right timing of irrigation water to avoid yield losses caused by drought stress.
3. The research findings will help farmers to determine the amount and timing of N fertilizer application in the case of hybrids with different maturity in order to achieve higher yields.
4. The information on the yield parameters of maize hybrids of different genotypes will help maize farmers to choose the appropriate maize hybrids for their purpose and to plan the recommended N application rate to increase the quality parameter that suits them.

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PUBLICATIONS ON THE SUBJECT OF THE THESIS



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A PhD értekezés alapjául szolgáló közlemények

Magyar nyelvű tudományos közlemények hazai folyóiratban (2)

1. Széles, A., **Horváth, É.**: Környezeti tényezők és az alap- és fejtrágyázás hatása a kukorica néhány fiziológiai tulajdonságára és a termésre.
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