Thesis for doctoral (PhD) dissertation

STUDY OF BIOLOGICAL TRAITS, PRODUCTIVITY AND YIELD QUALITY OF MAIZE HYBRIDS UNDER DIFFERENT STAND DENSITIES AND WATER SUPPLY CONDITIONS

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1. INTRODUCTION AND OBJECTIVES OF THE DOCTORAL RESEARCH

With the growing global population, agricultural production is facing increasing challenges. To achieve food security and sustainable agricultural development, increasing the efficiency of crop cultivation is of paramount importance. As the population continues to rise, consumption is expected to increase as well, making it crucial for crop yields to keep pace with growing demands.

Maize is one of the most important and widely cultivated crops globally. However, maize cultivation encounters various challenges, including climate change, water scarcity, nutrient deficiencies, as well as pest and disease management. Sustainable maize cultivation aims to produce high-quality products that meet food and feed safety requirements while considering environmental aspects. Achieving this goal requires the implementation of agronomically and economically efficient, hybrid-specific cultivation techniques. Rapid genetic advancements and a constantly changing hybrid portfolio necessitate cultivation technology investigations and experiments to uncover differences between individual genotypes, including determining the optimal plant density.

In recent years, climatic conditions have become increasingly unfavorable, with a decrease in the number of years with average precipitation and an increase in the frequency of drought years. As drought years become more frequent, the importance of irrigation is emphasized. One of the most critical factors affecting maize photosynthesis is water availability. Irrigated areas typically achieve higher yields than non-irrigated areas because irrigation improves plant water supply, allowing for more efficient photosynthetic processes. Additionally, irrigation supports the plant's metabolism, enhancing maize starch and protein yields per hectare. Irrigation enables plants to receive the appropriate amount of water for a given phenophase, which improves the quality and quantity of the crop. However, irrigation also comes with challenges, such as limited water resources, high costs, and environmental impacts.

Research results indicate that leaf area is closely related to maize growth and crop yield. The extent of leaf area can estimate the plant's photosynthetic capacity and water-use efficiency. Therefore, measuring leaf area is an important factor in improving the efficiency of maize cultivation.

This paper presents studies aimed at exploring the relationships between water supply, soil water management, maize growth, yield components, productivity, and quality parameters. Over three years (2019-2020-2021), we examined the efficiency of maize cultivation under irrigated and non-irrigated conditions, with four different hybrids and plant densities. The research focuses on maize plants' relative chlorophyll content, leaf area, vegetation index, crop yield, and quality. We tested hybrids with different genetic backgrounds but belonging to the same maturity group. We analyzed their agronomic characteristics, stress sensitivity, irrigation response, and changes in yield components.

Objectives:

- Analyzing the effects of different years on crop quantity and quality.
- Evaluating the impact of water supply on crop quantity and quality.
- Investigating the effects of plant density on crop quantity.
- Exploring and quantifying interactions between factors.
- Integrating our results into production, enabling agricultural practitioners to achieve both quantitative and qualitative improvements in maize crop yield and yield stability.

2. MATERIAL AND METHODS

2.1. Soil Characteristics of the Experimental Area

Location of the Experiment: University of Debrecen Farm and Regional Research Institute of Debrecen (FRRID) Látókép Experimental Station of Plant Production

The experimental station, established in 1983, is located on the Hajdúság loess plateau, 11 kilometers away from Debrecen, at the 95th kilometer marker of the 33rd main road (N: 47°33’42”; E: 21° 27’02”).

The soil of the experimental area is of excellent quality, well-cultivated, and belongs to the Alföld chernozem formation with limestone deposits. Physically, the soil can be classified as moderately compact loam (Arany's index of compactness ranges from 43.0 to 47.6). The humus layer thickness is 80-90 cm, with a uniformly humus-rich layer of 40-50 cm (humus content ranges from 2.16% to 2.76%). The pH of the soil (KCl) varies between 6.36 and 6.58 down to a depth of 75 cm, while deeper layers measure values between 7.27 and 7.36. The nitrogen supply of the area is moderate, with a total nitrogen content ranging from 0.12% to 0.15% down to a depth of 50 cm. The soil's potassium-supplying capacity varies between moderate and good (ranging from 173.6 to 239.8 mg kg^{-1} down to a depth of 50 cm). Phosphorus availability is good in the upper 25 cm layer (133.4 mg kg^{-1}), but less favorable in deeper layers (31.6-48 mg kg^{-1}).

The soil exhibits typical characteristics of chernozem soils, with favorable water management properties. The minimum water holding capacity ranges from 33.3% to 46%, and the wilting point ranges from 8.5% to 15.55% in the 0-200 cm layer. The soil is capable of storing a large amount of water, with the groundwater located at a depth of 3-5 meters.

2.2. Evaluation of Weather Conditions in the Study Years

For the development of maize, it is crucial to consider not only the amount of precipitation during the growing season but also the temperature and precipitation conditions in the preceding autumn-winter period. The natural water supply of the experimental area varied significantly in the study years, strongly influencing the development of the maize populations (Figure 2). In 2021, due to favorable water supply in the months of June to August, irrigation was not necessary, so we did not have the opportunity to evaluate the effects of irrigation in that year.

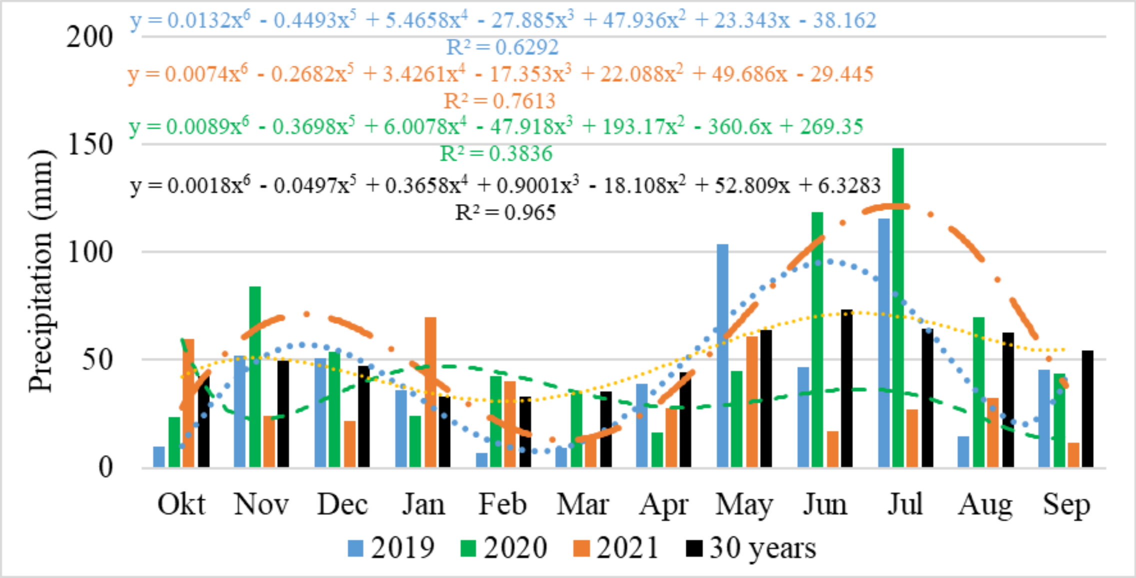

Figure 2: Precipitation Levels in the Experimental Years Compared to the 30-Year Average (1981-2010) (Debrecen, October 2018 - September 2021)

2.3. Field Experiment Conditions

Between 2019 and 2022, our small-plot maize experiment was conducted at the Farm and Regional Research Institute of Debrecen (FRRID) Látókép Experimental Station of Plant Production. In the experiment, we examined the development of four different maize hybrids, setting four different plant densities, under both dryland and irrigated conditions. We monitored changes in leaf area index (LAI), chlorophyll content (SPAD), normalized difference vegetation index (NDVI), productivity, yield-forming elements, and the quality of the grain (protein and oil content). Throughout the growing season, we determined soil moisture content based on soil samples taken at a depth of 200 cm, on multiple occasions.

Agronomic Conditions:

Plot Size: 1.52 x 10 m

The experiment was conducted with four plant densities in four repetitions, arranged in a 4-replication strip-strip block design. Two rows from each plot were harvested, while the third row served as the basis for in-season samples.

Uniform agronomic practices were employed, aside from the varying plant densities (65-75-85-95 thousand plants per hectare). Half of the plots received two irrigations of 25-25 mm of water around the tasseling period.

Previous Crop:
2019, 2021: Maize
2020: Soybean

Nutrient Management:
In the autumn, 30 kg ha $^{-1}$ N, 72 kg ha $^{-1}$ P_2O_5, and 72 kg ha $^{-1}$ K_2O were applied, followed by an additional 135 kg ha $^{-1}$ N in the spring.

Seeding was done with a pneumatic, single-seed drill on the following dates:
2019.04.18; 2020.04.16; 2021.04.08.

Harvesting was carried out with a SAMPO Rosenlew SR 2010 plot combine on 2019.10.17; 2020.10.08.; 2021.09.30.

2.4. Characteristics of the Examined Maize Hybrids in the Experiment

In my experiment, I used maize hybrids with similar maturation times: Kamária, KWS Kamparis, P9903, DKC4351.
Brief Description of the Examined Hybrids:
Kamária: A green-stalked hybrid with high stress tolerance. It is characterized by the erect leaf structure and excellent initial development vigor, although the young population typically exhibits a light green color. FAO 370.
Kamparis: A green-stalked hybrid with synchronized female and male flowering. FAO 350-400.
P9903: Bred for cultivation in Hungarian conditions, it tolerates high temperatures well during flowering and grain filling. FAO 390.
DKC4351: Exhibits good tolerance to plant density, rapid water release, and adapts well. Therefore, it can be successfully cultivated even under less favorable conditions. FAO 350.

2.5. Sampling and Calculation Methods

In situ Physiological and Developmental Studies:

The relative chlorophyll content was measured using the Minolta SPAD 502 Plus, the Normalized Difference Vegetation Index (NDVI) was assessed using the Trimble

Greenseeker handheld device, and the Leaf Area Index (LAI) was measured with the LICOR LI-2000 Plant Canopy Analyzer.

Soil Moisture Investigations:

Throughout the experimental years, soil samples were taken from irrigated and non-irrigated plots with plant densities of 65,000 and 95,000 plants per hectare for the P9903 and DKC4351 hybrids. Sampling was conducted down to a depth of 2 meters using the Kobra soil sampler, with samples taken in 20 cm intervals. Soil moisture content was determined using the thermogravimetric method. Wet soil samples weighing 100 g were placed in a drying cabinet and dried at 105 °C. After three days of drying, the soils were cooled back to 20 °C, weighed, and the soil moisture content was calculated from these measurements.

Quality Analysis of the Yield:

During the harvesting process, 3 kg samples were collected in a single pass. The moisture and content parameters were measured using the Pfeuffer Granolyser NIR grain analyzer. The thousand-seed weight was determined using the Pfeuffer Contador2 seed counter and a balance, and the weight was adjusted based on the seed moisture content at harvest.

The Determination of Potential Evapotranspiration (PET)

To establish the climatic water balance and assess the impact of the respective years, we calculated the value of potential evapotranspiration (PET).

The potential evapotranspiration was determined on a daily basis using the method developed by Gábor Szász, which takes into account atmospheric elements and processes that significantly influence water evaporation (SZÁSZ, 1997):

$$PET = \beta \left[0{,}0054\,(T+21)^2\,(1-R)^{\frac{2}{3}}\,f(v)\right], \quad (mm\;day^{-1})$$

A required data:

T: Daily average temperature (°C)

R: Relative humidity or saturation ratio (e/E)

β: Oasis effect factor

f (v): Wind speed effect function

The application of this formula to Hungary is recommended, as its development, validation, and certification are based on local data.

The determination of actual evapotranspiration (AET) considers the atmosphere's water absorbing capacity, soil moisture content, and the impact of vegetation (ANTAL, 1969).

$$AET = \frac{w+b}{1+b} * w * PET \qquad \text{[mm day}^{-1}\text{]},$$

Where:

w = the relative soil moisture content in the root zone (mm)
b = crop coefficient factor of maize
PET = the daily value of potential evapotranspiration (mm day^{-1})

Calculation of the w value:

$$w = \frac{W_a - WP}{W_{c\_}WP}$$

w: relative soil moisture content in the 0-200 cm layer (mm)
WP: permanent wilting point of the soil (mm)
Wc: field capacity of the soil (mm)

The calculations started with a 20 cm layer, and every 14 days, the root zone depth was increased by 20 cm, up to 1 meter.

2.6 Methodology for evaluating the results:

For data processing, the IBM-SPSS 26.0 statistical software package was used, employing analysis of variance (General Linear Model, GLM), linear and quadratic regression analysis, and Pearson correlation calculation. The calculation of Szd 5% values was performed using the method described by SVÁB (1981).

3. RESULTS

3.1 Changes in the water availability of maize crops

In the second and third decades of April (Figure 2), the actual evapotranspiration reached 38.8-34.4% of potential evaporation. Due to the large amount of precipitation in May, the AET/PET ratio improved to 67.4-67.8%, but this ratio decreased again to 47% at the end of June and beginning of July. In some of the measurement periods, the plants were visibly under water stress, which was confirmed by the measurements. Improved water supply in the second half of July resulted in a AET/PET ratio of 90.0% at the beginning of August.

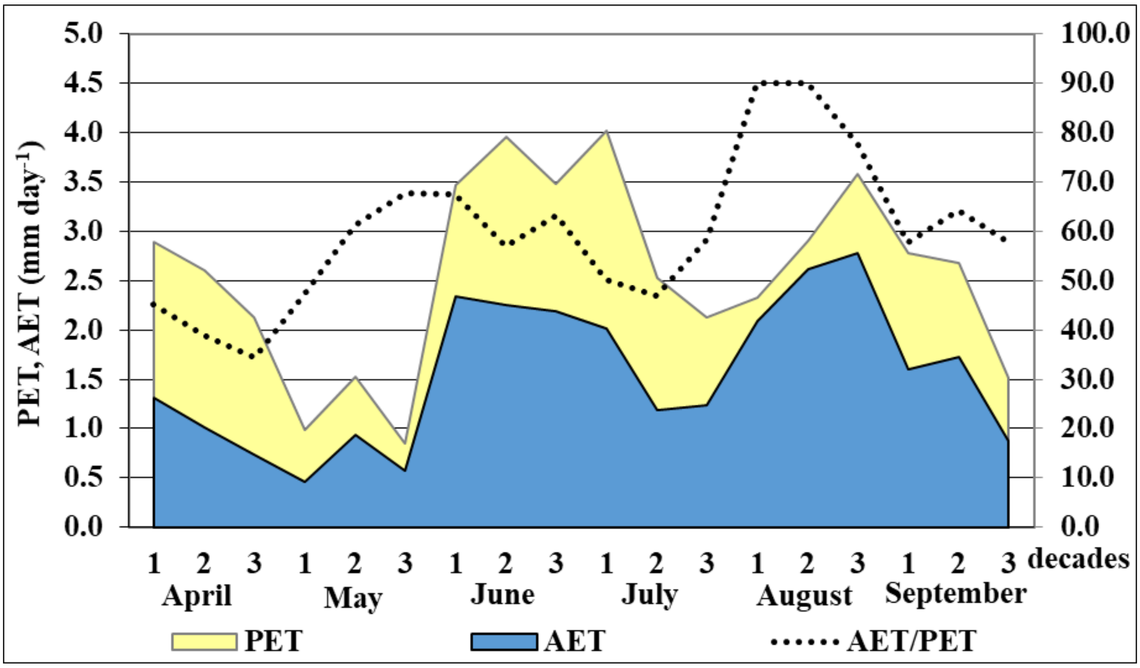

Figure 2: Estimated values of PET and AET, as well as the ratio of AET to PET in maize (Debrecen, 2019)

In 2019, the initial spring moisture supply was unfavorable due to the dry February and March, and at the time of sowing, soil moisture did not reach the minimum water holding capacity. By early June (Figure 3), the soil had dried out to the level of dead water content at a depth of 20 cm, but moisture could still be found in deeper layers for the maize plants. Thanks to the precipitation in June, the amount of water available for the plants increased by early July at depths of 0-60 cm. At a depth of 160 cm, soil moisture reached the starting moisture level from spring. By mid-August, in the non-irrigated plots, the amount of water in the soil had decreased below the dead water content level. The positive effect of irrigation was detectable up to a depth of 80 cm, while in deeper layers, the moisture levels were similar to those in non-irrigated areas.

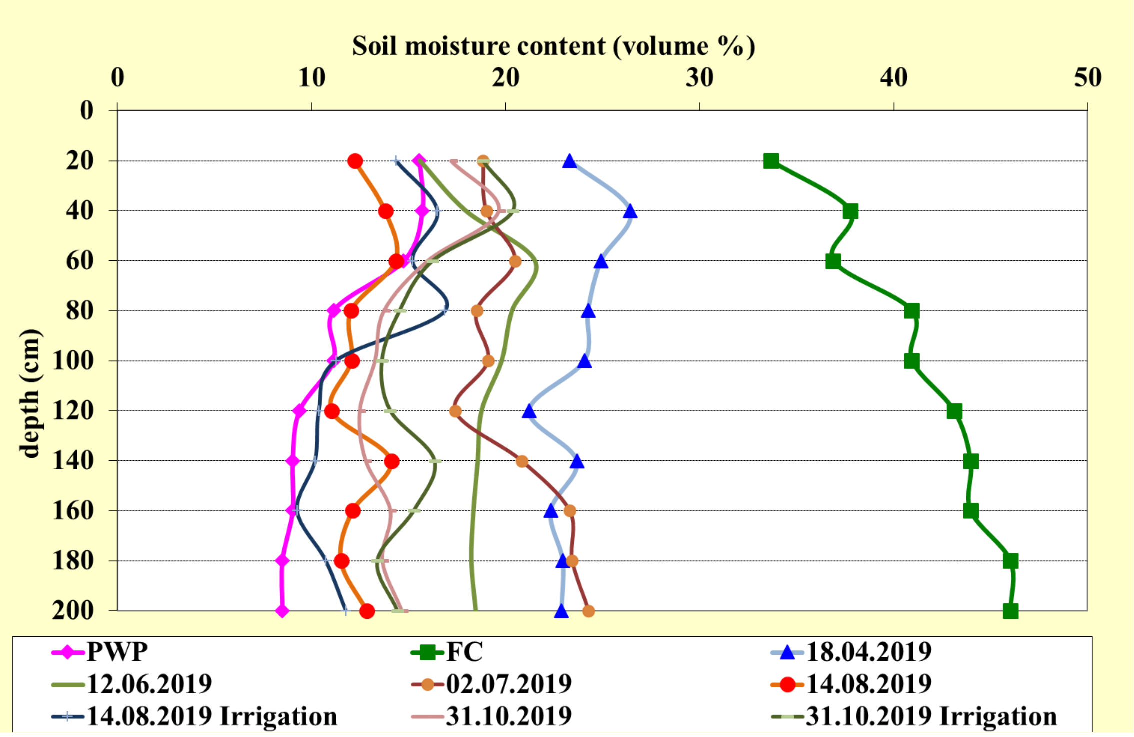

Figure 3: Volumetric soil moisture content ($cm^3\ cm^{-3}$) in the 0 – 200 cm layer in the maize experiment from 18 April to 31 October (Debrecen 2019) *FC: Field capacity PWP: Permanent Wilting Point*

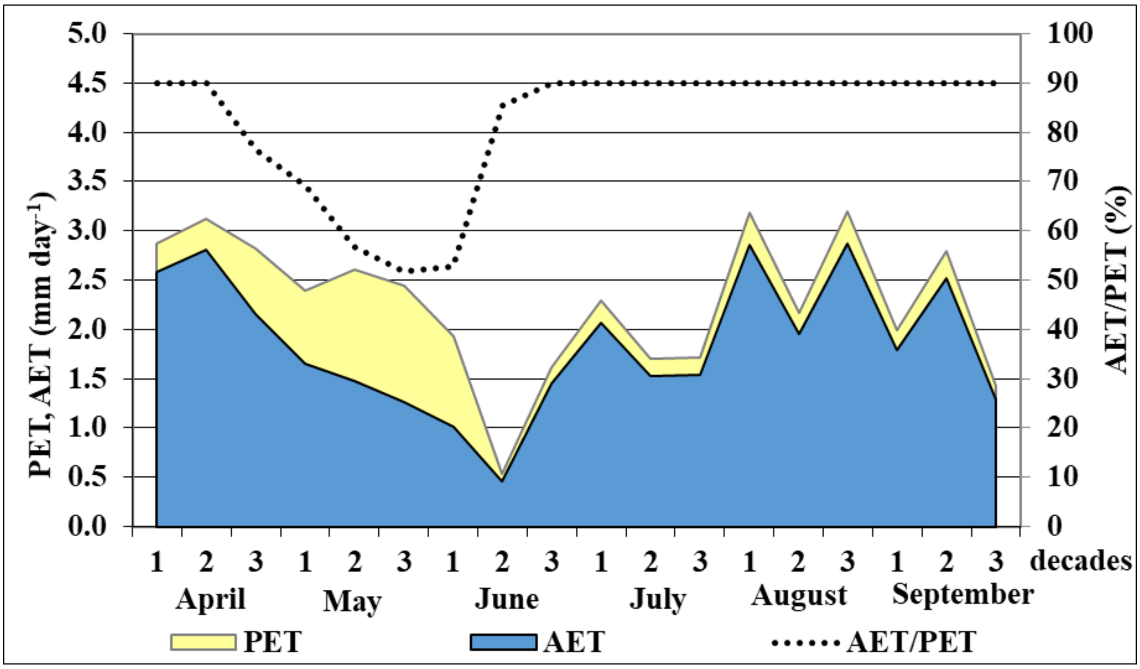

Figure 4: Estimated values of PET and AET, as well as the ratio of AET to PET in maize (Debrecen, 2020)

In the second and third decades of April, the actual evapotranspiration reached 76.3% of potential evaporation (Figure 4). Due to the low precipitation in May, the AET/PET ratio decreased to 51.9-52.7%. Improved water supply in the second half of June resulted in a AET/PET ratio of 90.0% at the end of June.

Due to the unusually favorable water supply, this ratio remained constant until the end of September. In most of the measurement periods, the plants were visibly not suffering from water shortage, which was confirmed by the measurements.

In 2020, the initial spring moisture supply was favorable due to a relatively rainy February and March after a rainy winter, and at the time of sowing, soil moisture reached the minimum water holding capacity level. By early June, the water content decreased at a depth of 20 cm, but the soil was in an ideal condition for the maize plants. Thanks to the precipitation in June, the amount of water available for the plants at depths of 0-60 cm remained very favorable by early July. By mid-August, soil moisture increased at depths of 40-80 cm in the plots. In deeper layers, the moisture levels only differed more significantly during the first and last measurements (Figure 5).

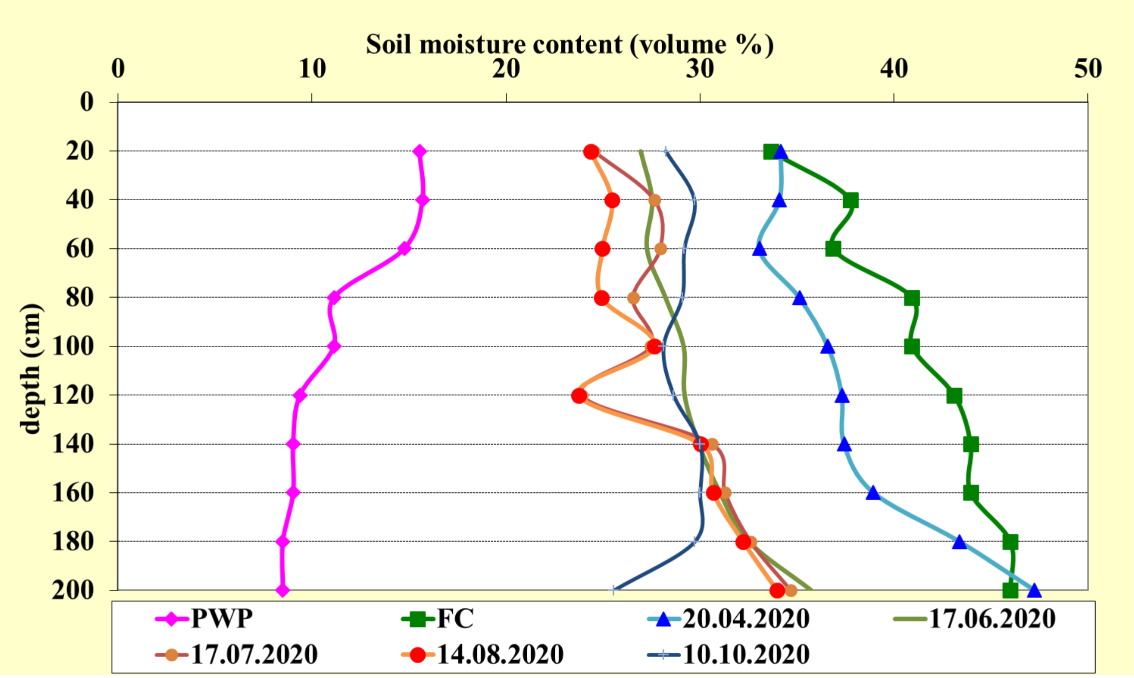

Figure 5: Volumetric soil moisture content (cm^3 cm^{-3}) in the 0 – 200 cm layer in the maize experiment from 20 April to 10 October (Debrecen, 2020) *FC: Field capacity PWP: Permanent Wilting Point*

In the second and third decades of April (Figure 6), the actual evapotranspiration reached 90% of potential evaporation. Due to the precipitation in May, the AET/PET ratio decreased to 89.3-84.8%, and this ratio decreased again to 84-66.1% at the end of June and beginning of July.

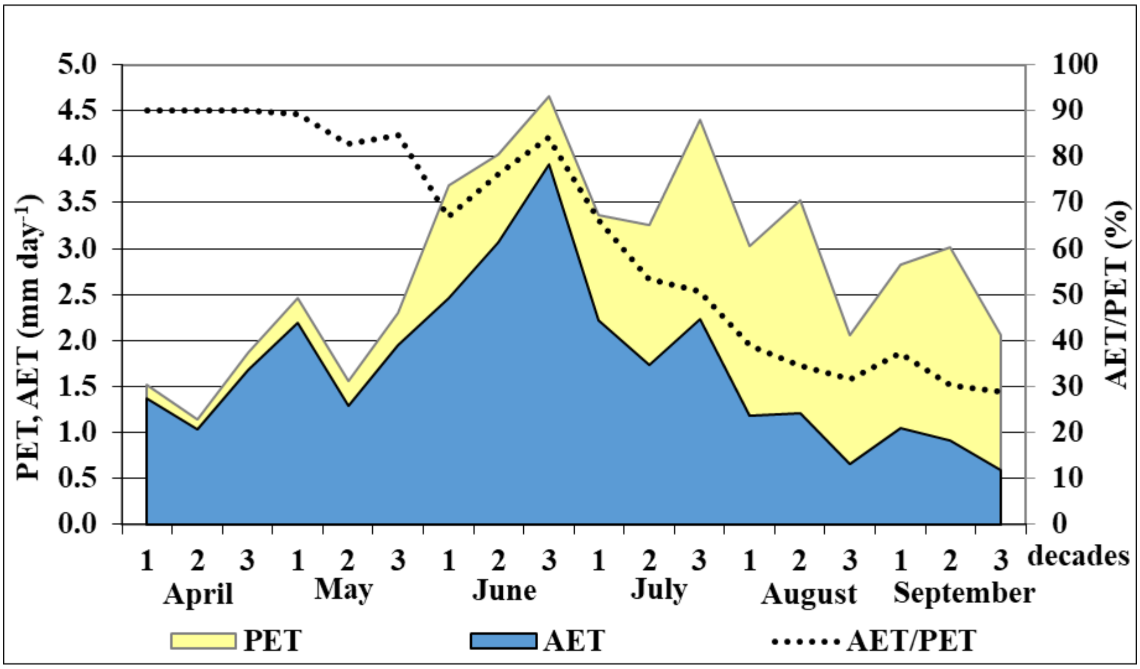

Figure 6: Estimated values of PET and AET, as well as the ratio of AET to PET in maize (Debrecen, 2021)

In some of the measurement periods, the plants were visibly in a water-stressed state, which was confirmed by the measurements. Deteriorating water supply in the second half of July resulted in a AET/PET ratio of 53.4-50.7% by early August. Due to the continued dryness in August and September, the AET/PET ratio further declined, reaching 28.8% by the end of September.

In 2021, the initial spring moisture supply was unfavorable due to the dry months of February, March, and April, and at the time of sowing, soil moisture did not reach the minimum water holding capacity level. By early June, the soil had dried out to the level of dead water content at a depth of 60 cm, but moisture could still be found in deeper layers for the maize plants. Due to the lack of precipitation in June (Figure 7), the moisture content remained below dead water content at depths of 0-60 cm by early July. By mid-August, in the non-irrigated plots, the water supply improved compared to the previous two months' data. The positive effect of irrigation, in most layers, resulted in moisture levels similar to those in non-irrigated areas.

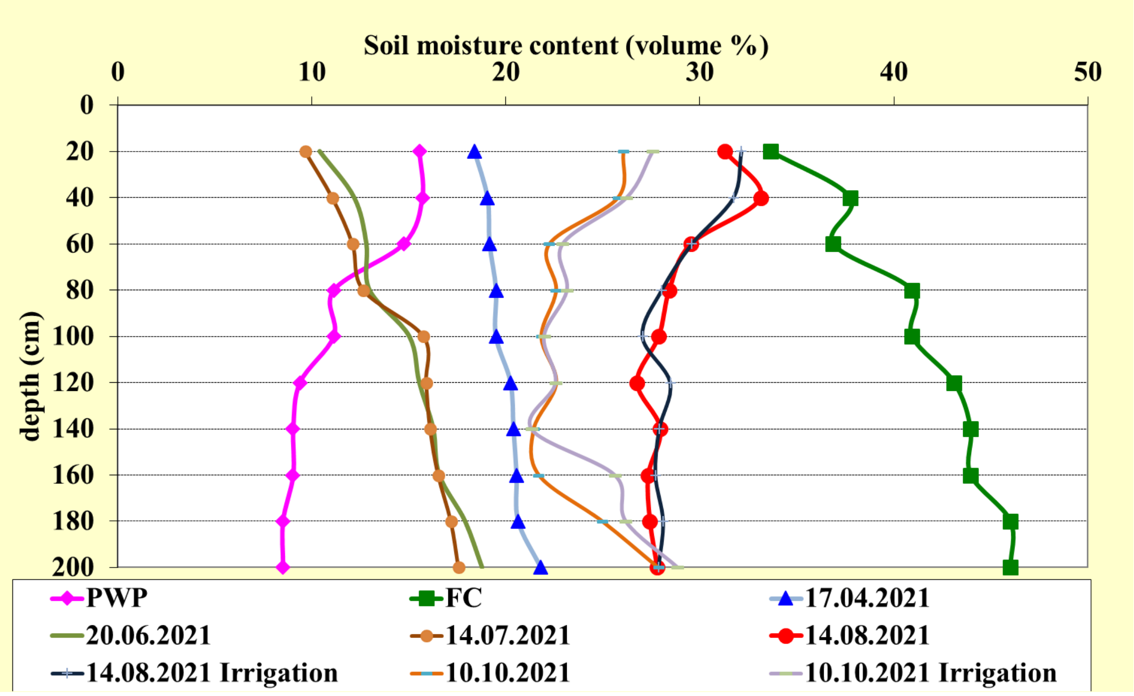

Figure 7: Volumetric soil moisture content (cm^3 cm^{-3}) in the 0 – 200 cm layer in the maize experiment from 17 April to 10 October (Debrecen, 2021) *FC: Field capacity PWP: Permanent Wilting Point*.

Out of the three examined years, irrigation was only conducted in 2019 and 2021, therefore the analysis of the effect of irrigation was carried out only with the inclusion of these two years.

3.2 The Effect of Water Supply and Plant Density on the Normalized Difference Vegetation Index (NDVI) of Maize Hybrids in 2019 and 2021

With different plant densities, no significant differences were found in the vegetation index for any of the water supply variants. However, without irrigation, the vegetation index decreased more significantly by the end of August with a plant density of 95 thousand per hectare, while in irrigated stands, the 65 thousand plant density proved to be less favorable.

When examining the irrigation response of hybrids in terms of NDVI values, there were no significant differences found among the examined genotypes in the average of two years (Figure 8). Similar to 2021, in the average of two years, without irrigation, there were differences between genotypes in the maximum NDVI values achieved during the peak vegetation period, while with irrigation, slightly greater differences were observed during the period of senescence. The P9903 hybrid, both with and without irrigation, maintained its vegetative surface slightly longer.

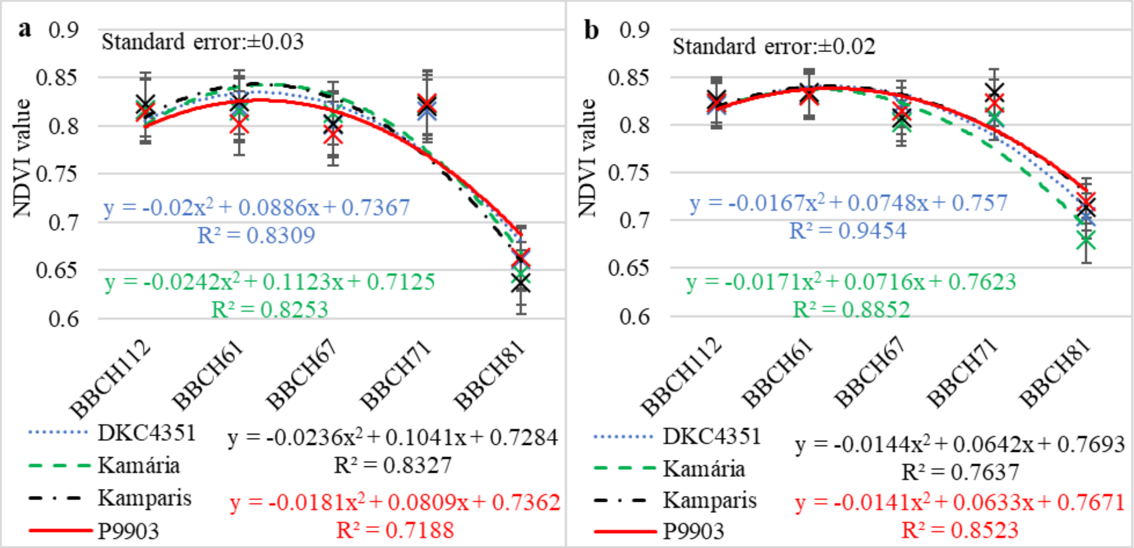

Figure 8: The Effect of Genotype on the Change in Normalized Vegetation Index under Different Water Supply Conditions (Debrecen, Average of 2019 and 2021) (a: non-irrigated, b: irrigated)

3.3 The Effect of Water Supply and Plant Density on the Leaf Area of Maize Hybrids in 2019 and 2021

When examining the effect of genotypes on leaf area in the average of two years (Figure 9), we found that due to irrigation, the hybrids achieved significantly larger leaf areas compared to non-irrigated conditions from BBCH67 development stage onwards. No differences were found between genotypes in any of the water supply variants.

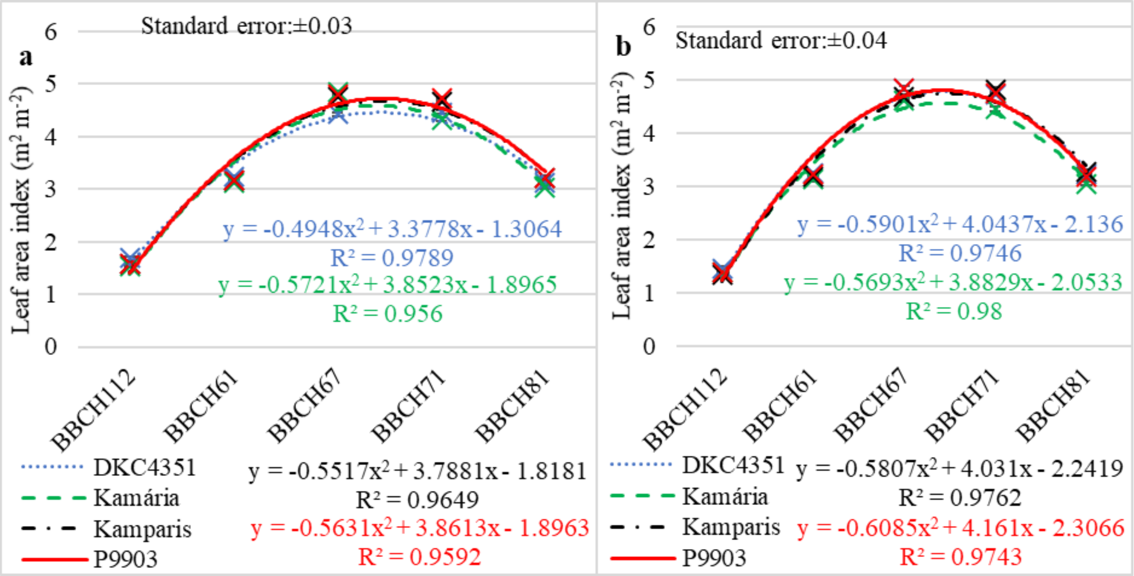

Figure 9: The Effect of Genotype on the Change in Leaf Area under Different Water Supply Conditions (Debrecen, Average of 2019 and 2021) (a: non-irrigated, b: irrigated)

3.4 Effect of Water Supply and Stand Density on Maize Hybrid Yields in 2019 and 2021

On average over the two years, P9903 achieved the highest yield (9946.88 kg ha^{-1}), however, this did not significantly differ from the yield of DKC4351 (9702.63 kg ha^{-1}). The difference in yield between DKC4351 and Kamparis (9489.75 kg ha^{-1}) is also not significant, and there is no significant difference between the yields of Kamparis and Kamária (9261.13 kg ha^{-1}).

The significantly lowest yield was observed at a plant density of 65 thousand plants per hectare. Compared to the 65 thousand (9104 kg ha^{-1}) plant density, a noticeably higher yield was obtained at 75 thousand (9697.13 kg ha^{-1}) plants per hectare. However, further increasing the stand density did not positively influence the yield.

The positive effect of irrigation on yield was confirmed for all hybrids (Figure 10). When examining the effect of plant density on yield (Figure 10), it was observed that in both irrigation treatments, significantly lower yields (8954.38 kg ha^{-1} and 9328.44 kg ha^{-1}) were recorded at a plant density of 65 thousand plants per hectare. There was no significant difference in yield among plant densities of 75-85-95 thousand. I observed that irrigation consistently led to an increase in yield.

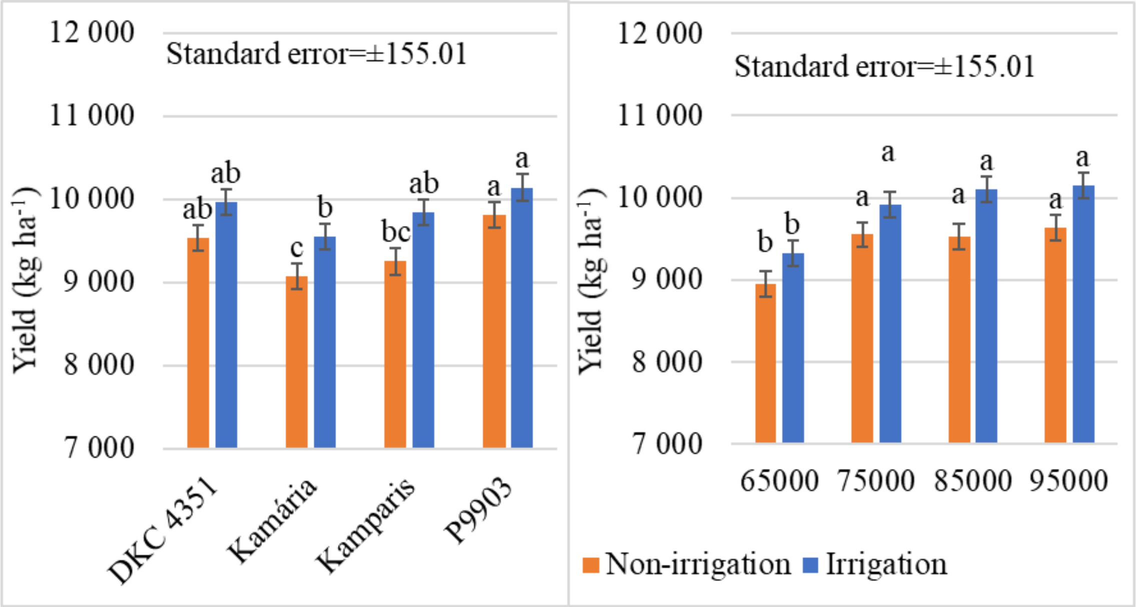

Figure 10: Effect of Water Supply on Maize Hybrid Yields in 2019 and 2021 *(Different letters within each treatment indicate significant differences between hybrids (10.a) or plant densities (10.b) p=5% significance level)* (Debrecen 2019 and 2021)

We also evaluated the individual plant density and irrigation response of the hybrids over the two-year average. The yield increased to varying degrees for all hybrids at every plant density due to irrigation.

3.5 Effect of Water Supply and Stand Density on the Quality of Maize Hybrids in 2019 and 2021

3.5.1 Effect of Water Supply and Stand Density on the Protein Content of Maize Hybrids in 2019 and 2021

At the lowest stand density, we measured a significantly higher protein content (8.64%). With an increase in plant density, the protein content decreased significantly (8.22%). Further densification of the stand did not have a significant impact on the protein content. Irrigation had an unfavorable effect on protein content for all genotypes (Figure 11). Without irrigation (8.6%) and with irrigation (8.33%), Kamparis achieved the highest protein content, however, it significantly differed only from the protein content of Kamária (8.30% and 7.84%).

The protein content decreased with irrigation for every hybrid and at every plant density. The highest protein content was clearly observed at a plant density of 65 thousand plants per hectare under non-irrigated conditions for every hybrid. However, for Kamária and

Kamparis hybrids, the 75 thousand plant per hectare stand density also proved favorable when irrigated.

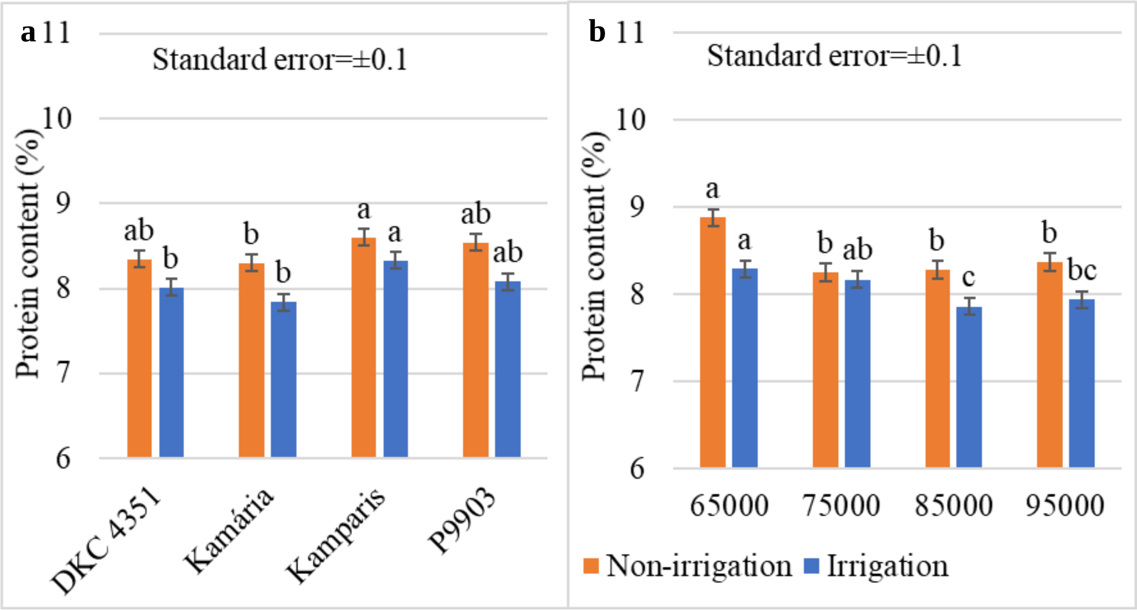

Figure 11: Effect of Genotype (a) and Stand Density (b) on Maize Hybrid Yields under Different Water Supply *(Different letters within each treatment indicate significant differences between hybrids (11.a) or plant densities (11.b) p=5% significance level)* (Average for Debrecen 2019 and 2021)

3.5.2 Effect of Water Supply and Stand Density on the Starch Content of Maize Hybrids in 2019 and 2021

Comparing the starch content of the hybrids, we found that Kamparis, which has exceptionally high protein content, achieved the significantly lowest value (75.07%). This result is not surprising, as numerous previous studies and our own experimental results have confirmed a tight negative correlation between protein and starch content.

Regarding stand density, we observed a precisely opposite relationship compared to protein content. Reducing the planting area has a more favorable effect on starch content.

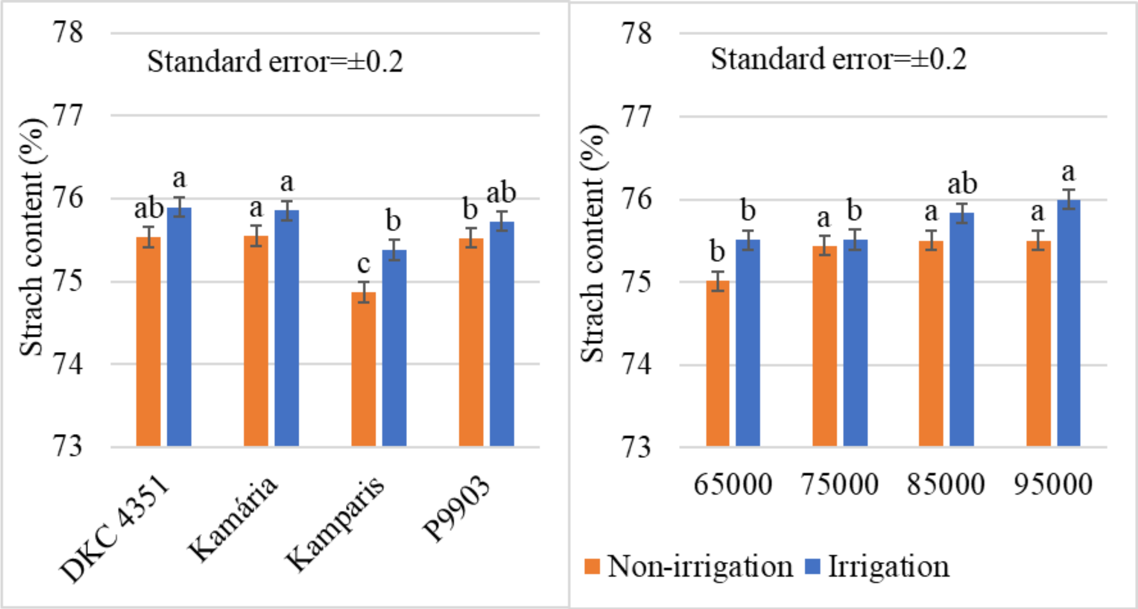

Figure 12: Effect of Water Supply on the Starch Content of Maize Hybrids in 2019 and 2021 *(Different letters within each treatment indicate significant differences between hybrids (12.a) or plant densities (12.b) p=5% significance level)* (Debrecen 2019 and 2021)

Analyzing the effect of irrigation on hybrids (Figure 12), it is evident that the starch content increased for all genotypes due to irrigation, although the magnitude of increase was smaller for the P9903 hybrid.

Without irrigation, the lowest plant density resulted in the lowest starch content at 75.01%, which was significantly lower than the starch content of 75.52% measured at a plant density of 75 thousand. Further increasing the stand density did not influence the starch content.

The starch content increased due to irrigation for most hybrids and at most plant densities, except for the P9903 hybrid at a plant density of 75 thousand (non-irrigated: 75.5%; irrigated: 75.25%), where a decrease in starch content was observed in the irrigated plots.

3.6 Effect of Water Supply and Stand Density on the Amount of Water Used to Achieve Unit Yield of Maize Hybrids

Water scarcity is becoming an increasingly prominent issue in agriculture, emphasizing the crucial importance of efficiently utilizing available water resources for plants. In plots without irrigation, we calculated the amount of precipitation received during the growing season (from sowing to harvest), divided it by the yield, and determined the amount of water used to produce 1 kg of grain. For irrigated plots, we added the amount of irrigation water applied to the amount of precipitation received during the growing season, and divided this total by the yield.

Table 1: Water Use Efficiency of Maize for Producing 1 kg of Grain (liters kg^{-1}) Considering Precipitation and Irrigation Water from Sowing to Harvest (Debrecen 2019-2021)

Plant density (piece ha^{-1})	Hybrid	Non-irrigation			Irrigation	
		2019	2020	2021	2019	2021
65000	DKC 4351	**417,8**	462,8	204,9	678,5	537,9
	Kamária	418,0	472,9	214,3	689,7	**626,5**
	Kamparis	**428,9**	**498,2**	**224,5**	**643,3**	605,5
	P 9903	427,3	**426,6**	**181,1**	**719,4**	**507,8**
	Average of hybrids	**423,0**	**465,1**	**206,2**	**682,7**	**569,4**
75000	DKC 4351	**403,6**	449,7	189,8	688,4	528,2
	Kamária	348,0	442,5	**223,4**	613,9	565,2
	Kamparis	**343,9**	**456,0**	206,8	**574,8**	**583,6**
	P 9903	402,5	**407,6**	**184,7**	**690,2**	**475,3**
	Average of hybrids	**374,5**	**438,9**	**201,2**	**641,8**	**538,1**
85000	DKC 4351	383,8	435,7	**182,8**	635,5	494,7
	Kamária	383,8	438,2	**234,0**	**649,2**	553,0
	Kamparis	**397,4**	**463,0**	205,0	**622,1**	**568,5**
	P 9903	**353,7**	**410,8**	196,2	629,9	**467,2**
	Average of hybrids	**379,7**	**436,9**	**204,5**	**634,2**	**520,8**
95000	DKC 4351	364,3	431,1	186,7	610,8	510,2
	Kamária	**424,1**	441,0	**225,1**	669,7	520,4
	Kamparis	**349,4**	**457,0**	199,6	**587,6**	**557,2**
	P 9903	418,7	**399,1**	**176,7**	**705,6**	**453,9**
	Average of hybrids	**389,1**	**432,0**	**197,0**	**643,4**	**510,4**
Average of plant density	DKC 4351	392,4	444,8	191,0	653,3	517,7
	Kamária	393,4	448,7	224,2	655,6	566,3
	Kamparis	379,9	468,5	208,9	606,9	578,7
	P 9903	400,5	411,0	184,6	686,3	476,1

In red font: the hybrid with the highest water consumption at the given plant number, with a pink background indicating the highest value among these. In blue font: the hybrid with the lowest water consumption at the given plant number, with a light blue background indicating the highest value among these. With a medium blue background: in the given year and treatment, the plant number where the water consumption was the lowest on average among the hybrids, while with a red background: the plant number where it was the highest. With a light yellow background: in the given year and treatment, the hybrid with the lowest average water consumption in plant numbers, and with a dark yellow background: the hybrid with the highest water consumption.

Based on the obtained results, we assessed which stand density and which hybrids managed resources most efficiently and used the least amount of water to produce unit yield.

In all experimental years, both in irrigated and non-irrigated treatments, on average, the hybrids showed the highest water use efficiency at a plant density of 65 thousand (206.2-682.7 l kg^{-1}) to produce 1 kg of maize grain (Table 1). In 2020 and 2021, the plants were most efficient in utilizing the available water resources at the highest plant density (197.0-510.4 l kg^{-1}). However, in 2019, without irrigation, the plant density of 75 thousand was the most favorable, while with irrigation, the plant density of 85 thousand proved to be the most efficient.

When evaluating the average plant densities, we observed that in both the favorably water-supplied year of 2020 and the dry year of 2021, the P9903 hybrid used the least amount of water to produce 1 kg of grain, both under irrigated and non-irrigated conditions (184.6-476.1 l kg^{-1}). In these years, regardless of the examined plant densities, this hybrid demonstrated the most favorable water use efficiency. The Kamparis hybrid managed the available water resources less efficiently, utilizing the most water (468.5-587.7 l kg^{-1}) to produce unit yield in both irrigated plots in 2020 and 2021.

The available water for the crops is not only represented by the precipitation during the growing season, but the precipitation during the winter semester can also be of significant importance, especially in the case of chernozem soils with excellent water management properties. Therefore, we calculated the amount of water used to produce 1 kg of grain yield, taking into account the amount of precipitation and irrigation water applied from August 1st of the preceding year until harvest (Table 2).

For the values measured from August onwards, I observed the same trend as when considering only the precipitation during the growing season, but the difference between the individual years in the amount of water used is significant. The difference between the 2019 and 2020 vintages is exacerbated by the water supply, as in 2020, the precipitation during the winter semester was also significant. With a population density of 65,000, considering the precipitation during the growing season alone, in 2020, there was 42.1 liters more water available for producing 1 kg of grain yield. However, when considering the precipitation during the winter semester as well, this difference increased to 352.4 liters.

Table 2. Maize water consumption for the production of 1 kg of grain yield (liter kg^{-1}) taking into account the precipitation and irrigation water from August 1st of the preceding year until harvest (Debrecen 2019-2021):

Plant density (piece ha^{-1})	Hybrid	Non-irrigation			Irrigation	
		2019	2020	2021	2019	2019
65000	DKC 4351	**473,3**	827,4	264,6	729,0	591,9
	Kamária	473,4	845,4	276,7	741,0	**689,4**
	Kamparis	**485,8**	**890,6**	**289,9**	**691,1**	666,3
	P 9903	484,0	**762,6**	**233,8**	**772,9**	**558,9**
	Average of hybrids	**479,1**	**831,5**	**266,3**	**733,5**	**626,6**
75000	DKC 4351	**457,2**	803,9	245,1	739,7	581,3
	Kamária	394,1	791,1	**288,5**	659,6	622,1
	Kamparis	**389,5**	**815,2**	267,0	**617,5**	**642,3**
	P 9903	455,8	**728,6**	**238,5**	**741,6**	**523,1**
	Average of hybrids	**424,2**	**784,7**	**259,8**	**689,6**	**592,2**
85000	DKC 4351	434,7	778,9	**236,1**	682,8	544,4
	Kamária	434,7	783,5	**302,2**	**697,5**	608,6
	Kamparis	**450,1**	**827,6**	264,7	**668,4**	**625,6**
	P 9903	**400,6**	**734,4**	253,3	676,7	**514,1**
	Average of hybrids	**430,0**	**781,1**	**264,1**	**681,4**	**573,2**
95000	DKC 4351	412,7	770,6	241,1	656,3	561,4
	Kamária	**480,3**	788,4	**290,6**	719,6	572,7
	Kamparis	**395,7**	**817,1**	257,8	**631,3**	**613,2**
	P 9903	474,2	**713,4**	**228,2**	**758,1**	**499,6**
	Average of hybrids	**440,7**	**772,4**	**254,4**	**691,3**	**561,7**
Average of plant density	DKC 4351	444,5	795,2	246,7	701,9	569,8
	Kamária	445,6	802,1	289,5	704,4	623,2
	Kamparis	430,3	837,6	269,8	652,1	636,9
	P 9903	453,6	734,8	238,4	737,3	523,9

In red font: the hybrid with the highest water consumption at the given plant number, with a pink background indicating the highest value among these. In blue font: the hybrid with the lowest water consumption at the given plant number, with a light blue background indicating the highest value among these. With a medium blue background: in the given year and treatment, the plant number where the water consumption was the lowest on average among the hybrids, while with a red background: the plant number where it was the highest. With a light yellow background: in the given year and treatment, the hybrid with the lowest average water consumption in plant numbers, and with a dark yellow background: the hybrid with the highest water consumption.

4. NEW SCIENTIFIC RESULTS

1. Among the maize hybrids studied, relative chlorophyll content (SPAD) and normalized differential vegetation index (NDVI) values were not statistically related to either stand density or genotypes in any of the water supply variants. In the unirrigated stands, maximum NDVI values (0.82-0.85) were always measured at the beginning of flowering (BBCH61), regardless of stand density. Irrigated stands continued to retain higher NDVI values during the rest of the growing season.
2. There was no clear correlation between NDVI values measured at different stages of development and yield in the years studied, but a significant positive correlation of medium strength (r = 0.588-0.632) was found between NDVI values measured at phenophases BBCH112-BBCH61 (2 leaf stage-flowering) and yield in the unirrigated stands in 2019 and 2020.
3. Irrigation significantly (p=1%) increased yield (353 kg ha^{-1} - 1161 kg ha^{-1} yield increase). The best irrigation response over the years was observed for the hybrid Kamparis (597.29 kg ha^{-1}), while the lowest yield increase was obtained for the hybrid P9903 (323.96 kg ha^{-1}). The interaction between genotype and irrigation was not significant in any of the experimental years.
4. The protein content of the grain yield differed significantly among the hybrids on average over the three years (p=0.02), with the highest protein content in the Kamparis hybrid (8.47%) and the lowest in the Kamaria hybrid (8.07%). The effect of irrigation on protein content was significant at the p=1% level. Higher protein content was measured in the non-irrigated treatment (8.45% on average). The effect of irrigation reduced the protein content to 8.06% on average.
5. Irrigation significantly increased the starch content at the p=1% level, but the difference was not significant on average over three years (irrigated: 75.72% and non-irrigated: 75.37%). The highest starch content was found in hybrid DKC 4351 (75.72%).
6. Evaluating the water usage of the examined genotypes on average of plant densities, we determined that the P9903 hybrid exhibited the lowest water consumption (184,6-476,1 l kg^{-1}) in both well-watered conditions in 2020 and drought conditions in 2021, under both irrigated and non-irrigated

circumstances.m. Meanwhile, the Kamparis hybrid utilized the most water, ranging from 468.5 to 587.7 liters per kilogram, to produce the same quantity of yield.

5. PRACTICAL USE OF THE RESULTS

1. Based on the three years of study, it is recommended to use a plant density of 75,000 plants per hectare for FAO 350-400 maturity group hybrids on chernozem soil. This density resulted in significantly higher yields (At a plant density of 65,000 plants per hectare: Unirrigated yield 8.95 t ha^{-1}; Irrigated yield 9.33 t ha^{-1}; At a plant density of 75,000 plants per hectare: Unirrigated yield 9.55 t ha^{-1}; Irrigated yield 9.92 t ha^{-1}) in both irrigation conditions compared to the lowest density of 65,000 plants per hectare. Further increasing plant density did not lead to significant yield increases in any case, even in irrigated plots, and in drier years, it caused yield depression.
2. For the Kamária and Kamparis hybrids, plant densities exceeding 75,000 plants per hectare are not recommended (Kamária 75000: Unirrigated 9.44 t ha^{-1}; Irrigated 9.87 t ha^{-1}; Kamária 85000: Unirrigated 9.1 t ha^{-1}; Irrigated 9.67 t ha^{-1}; Kamparis 75000: Unirrigated 9.6 t ha^{-1}; Irrigated 10.11 t ha^{-1}; Kamparis 85000: Unirrigated 9.19 t ha^{-1}; Irrigated 9.78 t ha^{-1}), even in irrigated plots, as they do not lead to yield increase. In many cases, especially in non-irrigated plots, higher plant densities actually caused yield depression.
3. The P9903 (10.27 t ha^{-1}) and DKC4351 (10 t ha^{-1}) hybrids achieved the highest yields in the 85,000 plant per hectare density in multiple years, although this yield increase was generally not statistically significant. Therefore, plant densities greater than 75,000 plants per hectare are not recommended for non-irrigated cultivation. In irrigated cultivation, plant density can be increased up to 85,000 plants per hectare.
4. In most of the studied years, the P9903 hybrid (9.95 t ha^{-1}) yielded significantly more than the other hybrids, although its yield advantage over the DKC 4351 (9.7 t ha^{-1}) hybrid was not statistically confirmed on average over the three years.
5. The good yield potential of the P9903 hybrid is coupled with favorable protein content (8.36%) in the grain, allowing for a higher protein yield per hectare on average over multiple years.
6. On average over the experimental years, the starch content (75.07%) in the grain of the Kamparis hybrid was significantly lower than in the other hybrids, making it less suitable for bioethanol production.

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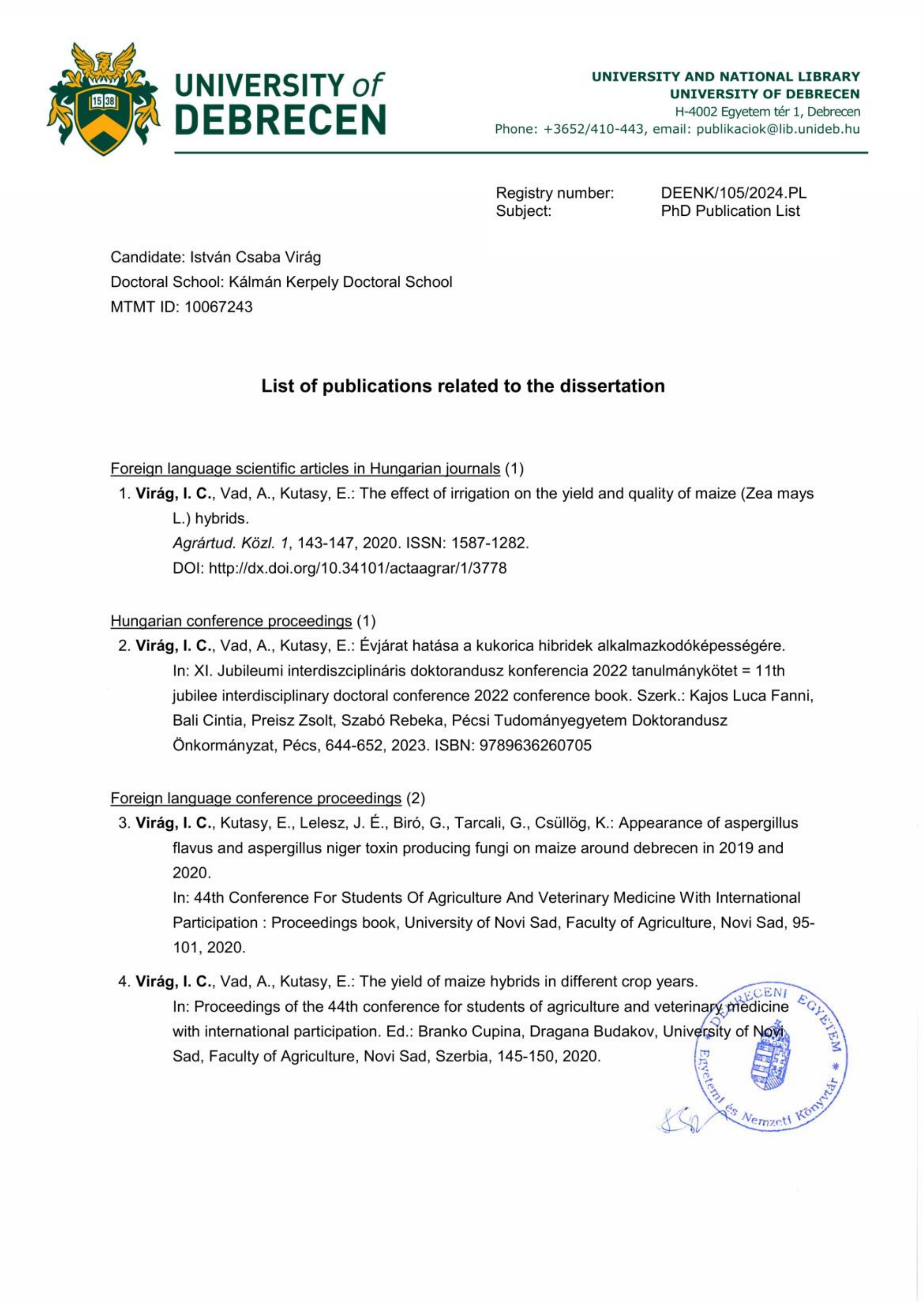
7. PUBLICATIONS ON THE SUBJECT OF THE THESIS



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Candidate: István Csaba Virág
Doctoral School: Kálmán Kerpely Doctoral School
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List of publications related to the dissertation

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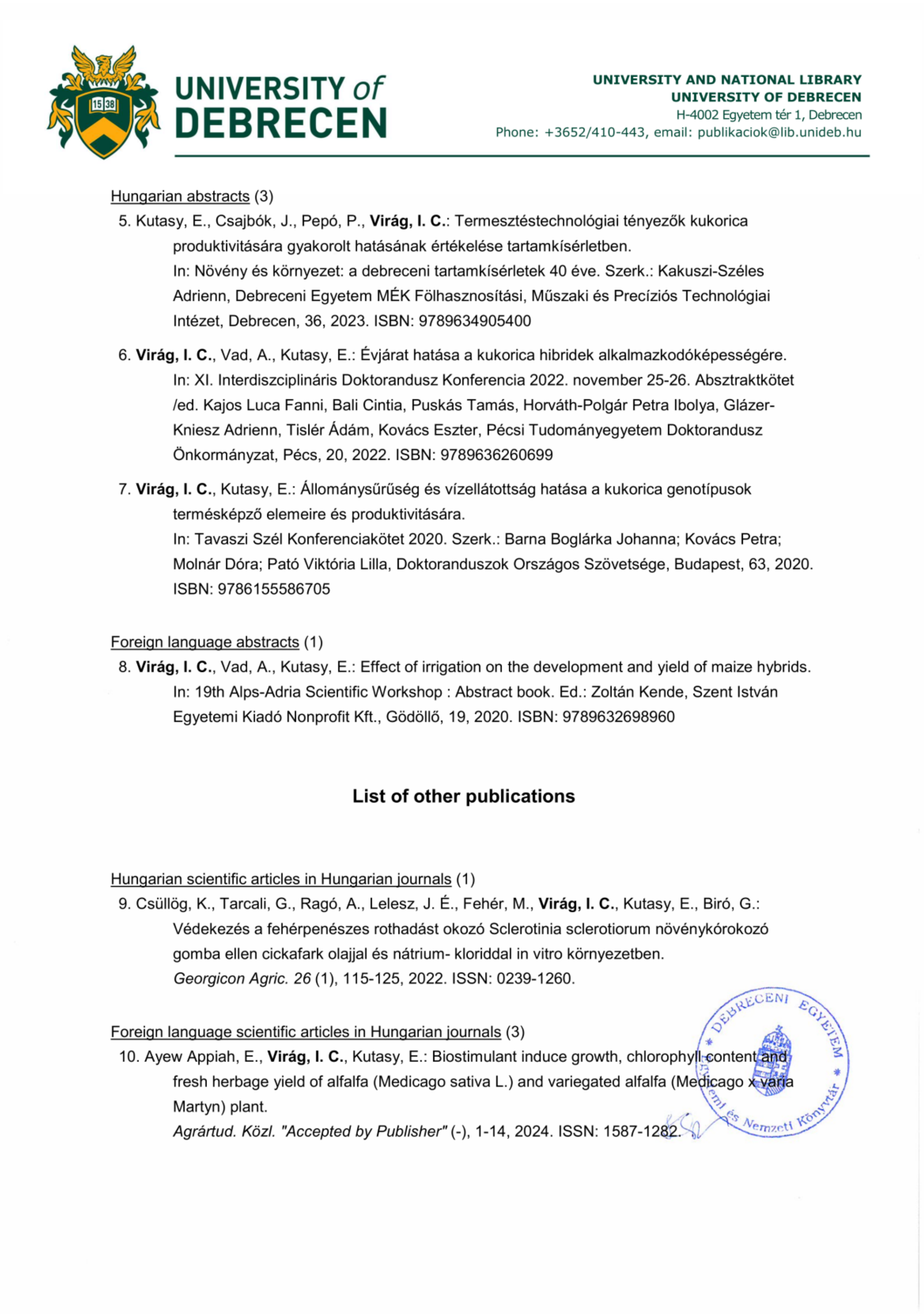

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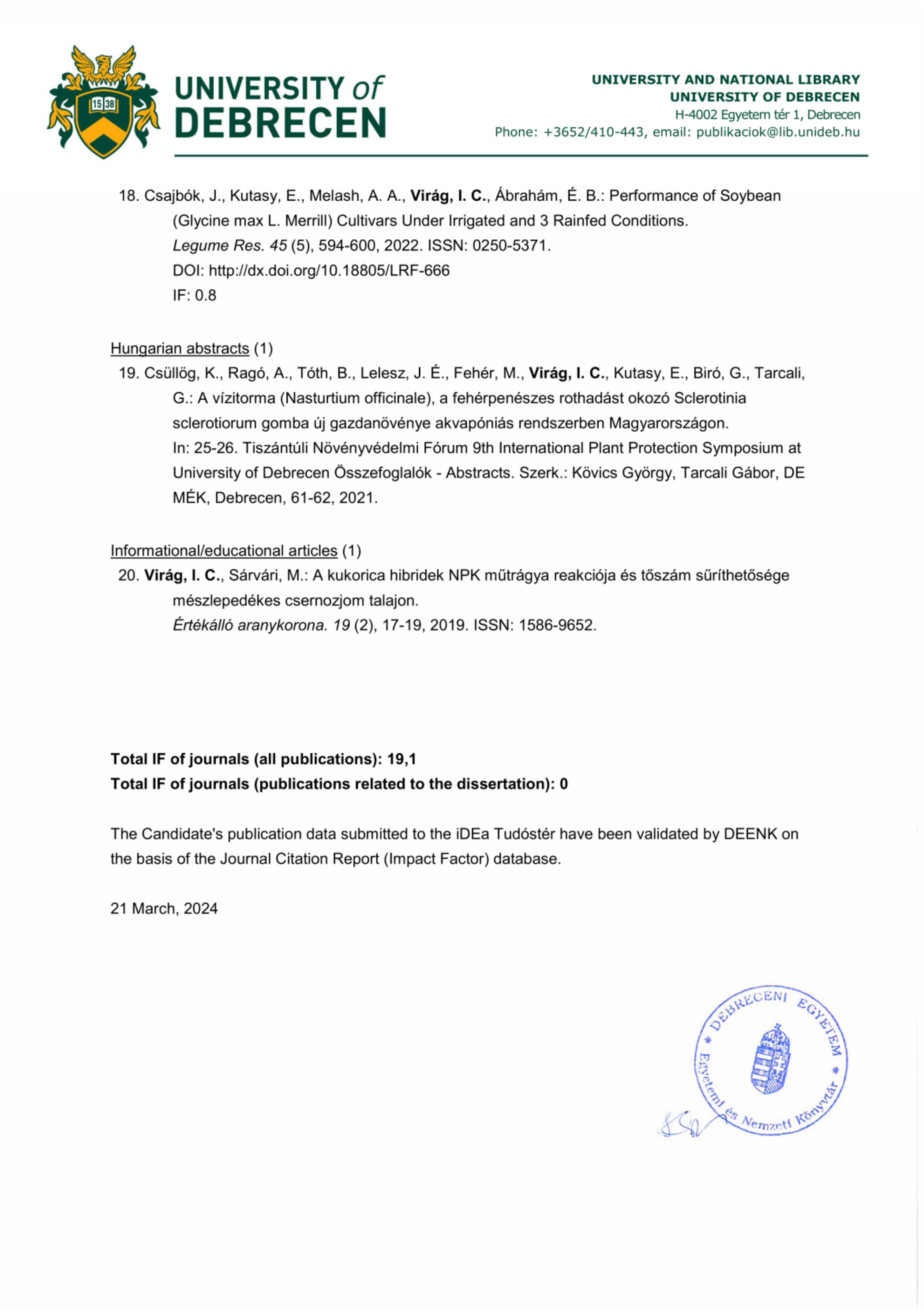

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Total IF of journals (publications related to the dissertation): 0

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

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