

Theses for doctoral dissertation (Phd)

COMPARATIVE STUDY OF MAIZE HYBRIDS WITH DIFFERENT GENOTYPES

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1. Background and objectives of the dissertation

Maize is one of the most important cultivated crops in Hungary. However, its yield is highly dependent on the prevailing weather conditions of a given year. The historic drought of 2022 clearly demonstrates the increasing importance of ensuring yield stability and security in maize cultivation. Global maize production has significantly increased in recent decades, driven by growing demand and advances in technology. This was achieved through a combination of yield improvements and the expansion of cultivated areas. Maize is currently one of the leading cereal crops in terms of production volume, and it is expected to become the most widely cultivated and most sought-after crop in the coming years (Erenstein et al., 2022).

Higher yields can be achieved through appropriate nutrient management, while yield security can be ensured through proper water management. A significant agricultural consequence of the general atmospheric warming associated with climate change is that the growing conditions for crops will change.

Researchers have developed numerous methods to evaluate and improve the efficiency of agricultural production. One such method widely used in practice is the measurement of chlorophyll content and vegetation indices in plants. These indicators help assess the condition of plants and thus evaluate the effectiveness of irrigation.

Maize yield security is determined by the combined effects of ecological factors, biological bases and agrotechnology, all of which are closely interrelated. The biological bases have significantly improved thanks to plant breeding: more than 300 maize hybrids are officially cultivated in Hungary, and EU-certified seeds are also available. The use of hybrid seeds has greatly contributed to the success of maize production (Ignacio and Ciampitti, 2014). Yield potential is a key criterion when selecting hybrids. Today's hybrids are technologically advanced and available in various maturity groups (FAO 200-600 group). The length of the growing season is influenced by temperature; thus, a relationship exists between heat units and maturity time. Compared to the growing season measured in days, heat units provide a more precise characterization of hybrid performance, as day-based measurements can vary annually even under the same growing conditions. Therefore, classifying hybrids based on heat unit requirements is becoming increasingly widespread.

For agricultural crops, uneven rainfall distribution - as an abiotic stress factor - requires growing attention. In previous decades, annual precipitation was never fully sufficient, covering only 50-80% of the water needs of field crops. With rising temperatures, longer dry periods,

and unpredictable or low precipitation, soil moisture levels decrease. This poses a clear threat to continuous water supply and the physiological functions of crops (Vágó et al., 2006; Stekauerová and Nagy, 2006; Ruzsányi, 1996). Nearly two decades ago, Olesen and Bindi (2002) emphasized that the increasing frequency of drought and extreme weather in Europe would result in lower yields, greater yield variability, and reduced areas suitable for conventional crops.

Both now and in the future, maize varieties will need to maintain yield stability even under extreme weather conditions. However, this requires expert knowledge and the ability to determine which agrotechnical practices are optimal under specific ecological and economic conditions. In the future, sustainable maize production will depend heavily on research and innovation.

In my dissertation, I present research focused on understanding the relationships between maize development, yield components, productivity and quality parameters. During my research, I examined the efficiency of cultivation in irrigated maize culture for 4 years (2020-2023) in five different genotypes. My research focused on relative chlorophyll content, leaf area, vegetation indices, phenometric parameters, and yield quantity and quality. Special attention was paid to agronomic traits of hybrids, changes in yield components, water release capacity, and the accumulation of heat units during various phenological stages, from germination to harvest. The experiment included hybrids from different genetic backgrounds and maturity groups. Yield security and stability can be increased by choosing a hybrid that is adapted to the growing location and by applying professional hybrid-specific agrotechnology that meets the needs of the plant. (Pepó, 2006).

The most important objectives of my research are:

- analysis of the effects of the years and vintages examined, their effects on yield,
- the effect of the vintage on the developmental phases of individual maize hybrids (heat sum, emergence, flowering, physiological maturity),
- quantification of the phenotypic appearance of hybrids, the effect of vintage and cultivation factors on yield and yield elements,
- observation of water yield of genotypes, considering the vintage as an influencing factor,
- exploring and quantifying the interactions between factors,
- modelling of maize yield and comparing it with practical results,
- by integrating the results into production, farmers can achieve qualitative and quantitative improvements in maize yield and crop security.

2. Material and methods

2.1 Location, soil conditions and parameters of the experimental area

My measurements were conducted at the Látókép Experimental Station of the University of Debrecen, in a long-term experiment established in 2018. The research was carried out during 2020, 2021, 2022, and 2023. The site is located approximately 15 km from Debrecen, next to Main Road 33. The experimental area is flat and homogeneous, and the soil is classified as calcareous chernozem according to soil genetics. It is of good quality, well-cultivated, with good water retention and moderate water-holding capacity.

2.2 Climate characteristics of the experimental area

The weather of the experimental period (breeding years 2020-2023) was analysed on the basis of air temperature and precipitation data from the automatic meteorological station of the Institute of Earth Utilisation, Engineering and Precision Technology at the University of Debrecen. For the deviations from the long-term averages, the climate averages of the National Meteorological Service Debrecen-Airport station for the period 1981-2010 were used as a reference. The detailed agro-meteorological analysis of each year (covering several meteorological elements, presented in decadal and partly in daily resolution) for maize and for the Debrecen region is based on the results of Nagy and Nagy 2022, Gombos and Nagy 2022, Gombos and Nagy 2023, mainly using monthly data to present the weather conditions of the experimental years.

Overall, of the four years studied, one was highly favourable, one good, and two highly unfavourable for maize cultivation in the Debrecen region (Gombos and Nagy, 2024b). The 2020 growing season was nearly optimal due to abundant and well-distributed rainfall and average summer temperatures. In contrast, 2021 experienced severe drought due to the lack of deep soil moisture and high temperatures. The record-breaking drought of 2022 was caused by hot, nearly rainless conditions and very low initial soil moisture. In 2023, the starting soil water content matched field capacity, and the season featured moderate temperatures and average rainfall, providing favourable agrometeorological conditions for maize.

2.3 Presentation of the experiment

In the experiment, the tested hybrids were included in one repetition. Identical agrotechnical practices were applied across all plots. The total experimental area was 0.33 hectares. The setup included a 15 cm plant spacing and 75 cm row spacing, resulting in a plant density of 84,000 plants per hectare. The irrigation technology used was drip irrigation (Figure

1). Each year, the system was installed in the early vegetative stage (8–10 leaf stage). The total irrigation water applied during the breeding season was 152 mm (2020), 304 mm (2021), 456.8 mm (2022), and 374 mm (2023). Fertigation was used during the growing season to provide sufficient nutrients.



Figure 1: Drip irrigation equipment (Debrecen-Látókép)

Hybrids included in the experiment

Hybrid notation	FAO number	Years
H1	420	2020.,2021.,2022.,2023.
H2	390-410	2020.,2021.,2022.,2023.
H3	350-360	2020.,2021.,2022.,2023.
H4	490	2020.,2021.,2022.
H5	490	2023.

During the vegetative phase of maize, the following characteristics were recorded:

Germination (number of days from sowing, date), *Crest bloom*, *Silking*, *Plant height* (cm), *Ear height* (cm), *Stem diameter* (mm), *Leaf area index*, *Black Layer test*

Grain water release test: 50-100 grains were first measured wet, then dried at 60 °C until reaching constant weight in a drying cabinet. The difference determined the moisture content.

SPAD and NDVI measurements: Conducted four times per season (6-leaf; 12-leaf; silking; physiological maturity).

Measurement of generative parameters, yield and quality of maize:

For the crop element studies, individual samples were taken by genotype after physiological maturity. In order to accurately determine the ear parameters, the crop samples were processed with a Haldrup grain laboratory thresher (grain number, thousand-grain weight,

ear, grain and cob weight, grain-to-cob ratio). Before crumbling, the length and diameter of the corn ears were measured on the samples. The content values were examined with an NIR device, the FOSS Infratec Grain Analyzer. The data (based on the total weight of the sample) gives the moisture content in mass percent, and the starch, protein and oil content in relation to the dry matter content, also expressed in mass percent.

The amount of heat required for the tests was calculated centrally from the averages of the daily temperatures “Tmin” and “Tmax”, the base temperature was 10°C. (If Tmin<10, then Tmin=10, and if Tmax>30, then Tmax=30 was used in the calculation.)

2.4 Statistical analysis of experimental data

Before statistical analysis, data normality was tested using the Kolmogorov-Smirnov test. The effect of factors (year, genotype, phenophase) on plant parameters was analysed using one- and multi-way ANOVA. Significant differences were tested using Fisher's LSD. Minitab 22 statistical software was used for statistics, and MS Excel 2019 for charts. Pearson correlation analysis was conducted to assess the relationships between measured parameters.

2.5 Methodology of the DSSAT Ceres-Maize program application

I used the Ceres-Maize model of the DSSAT v4.7 software (Jones et al., 2003) to evaluate the data and model the yield. This model is suitable, among other things, for mapping the value of plant production (biomass and grain yield) and leaf area. The system calculates and provides results on a daily scale, and accordingly its data requirements for weather are also detailed on a daily basis. Accurate meteorological data of the experiment, detailed soil test data, hybrids used and agrotechnical operations are required for running. The agrotechnical operations performed (soil cultivation, sowing, fertilizer application, harvesting method and times, etc.) were used.

I provided the necessary information based on relevant data in the simulation, i.e. according to the agrotechnical times (e.g. sowing time in the given year and harvesting time). In accordance with the applicability of Ceres-Maize, we used Ritchie and Ritchie-Ceres (Priestley-Taylor/Ritchie) algorithms to describe evaporation, model processes in the soil, run water capacity values, and determine evapotranspiration (Nyéki et al., 2020).

Meteorological data

The parameters required for the model were: minimum temperature (°C), maximum temperature (°C), precipitation (mm), global radiation value (MJ/m²), relative humidity (%) and average wind speed (m/s).

Soil data

I used the Soil Data module (SBuild) to adapt the coordinates, soil profile and classification of the site. The measured soil characteristics were used to calculate the soil physical and chemical parameters required for yield prediction (model running).

Genetic parameters of the hybrids tested

The necessary quantified data to define a hybrid are as follows. P1 is the effective heat required until the end of the juvenile phase (°C day), parameter P2 represents the photoperiodic sensitivity, P5 represents the heat from silking to physiological maturity (°C day), G2 represents the number of grains on one tube, while parameter G3 represents the maximum rate of dry matter incorporation (mg/day) and the interval between the appearance of successive leaf tips in degree days (PHINT).

3. Results

Phenological parameters:

Regarding the parameters examined, a significant difference can be detected between the hybrids and vintages used in the experiment (Table *I*). Plant height and stem height are influenced by both vintage and their combined effect ($P < 0.001$). The highest plant and stem height and stem diameter, as well as the average of the hybrids, were measured in 2023 (322 cm- 138 cm- 20 mm).

Table 1: Phenological parameter results of hybrids across years
Debrecen-Látókép (2020-2023)

Parameters	Years	Hybrids		
		H1	H2	H3
Plant height (cm)	2020	285,3 ^{bc}	290,1 ^b	268,1 ^d
	2021	264,0 ^d	285,0 ^{bc}	279,5 ^c
	2022	293,0 ^b	317,8 ^a	318,9 ^a
	2023	313,9 ^a	323,0 ^a	321,8 ^a
Ear height (cm)	2020	117,1 ^{ef}	118,2 ^{ef}	111,7 ^f
	2021	101,4 ^g	112,3 ^f	116,8 ^{ef}
	2022	123,9 ^{de}	132,9 ^{bc}	133,2 ^{bc}
	2023	127,4 ^{cd}	150,0 ^a	140,4 ^b
Stem diameter (mm)	2020	18,04 ^{bc}	17,48 ^c	18,33 ^{bc}
	2021	18,55 ^{bc}	17,02 ^c	20,43 ^a
	2022	18,11 ^{bc}	20,29 ^a	19,43 ^{ab}
	2023	20,35 ^a	20,84 ^a	20,58 ^a
LAI	2020	4,1 ^{de}	4,3 ^{bcde}	4,2 ^{cde}
	2021	5,0 ^{bc}	4,3 ^{bcde}	3,8 ^e
	2022	5,0 ^b	4,8 ^{bcd}	4,2 ^{de}
	2023	6,4 ^a	7 ^a	7,4 ^a

Different letters for different parameters indicate statistically proven differences between both hybrids and vintages ($p = 5\%$ level).

The highest plant height was for the H2 (323 cm) and H5 (329.5) hybrids. The highest ear height was obtained for the H2 hybrid in 2023 (150.0 cm). The thickest stem was recorded for the three hybrids in 2023, all three hybrids showed results above 20 mm. The maximum value was measured for the H2 hybrid (20.84 mm). Plant height was in a positive medium correlation with yield (2021: $R = 0.496^{**}$; 2022: $R = 0.329^{*}$; 2023: $R = 0.411^{**}$). Based on the results examined, it can be stated that leaf area plays a decisive role in the yield of corn hybrids

in different years. I measured maximum leaf area values in 2023 (H3 hybrid 7.4), the lowest leaf area was obtained for the same hybrid in the 2021 growing year (3.8). In all three years of the study, the leaf area index was in a positive medium (0.339*; 0.48*; 362*) correlation with the yield. Based on my results, it can be said that 2023 was the most suitable year in terms of the development of phenological parameters, considering the genotypes included in the experiment.

SPAD and NDVI values:

The results are consistent with findings from Ványiné (2009), who concluded that both fertilization and the year significantly influenced SPAD values. The highest SPAD readings at the 6-leaf stage were recorded in 2023, especially in H2 (39.31). The lowest value was measured in H1 in 2021 (29.1). At the 12-leaf stage, year-to-year variation became more pronounced, with 2020 showing the highest SPAD values (H2: 60.5), and 2022 the lowest. McMaster's (1997) finding was observed over the four years, as there was a significant difference between the SPAD values of maize of different ages and leaves, with values measured in the pre-flowering stage being significantly higher and decreasing after flowering.

Based on the independent and joint effects of the individual experimental parameters examined, such as genotype, year and different phenological stages, it can be stated that the combined effects of year, genotype, phenophase, year x hybrid, year x phenophase, hybrid x phenophase and year x hybrid x phenophase had a significant ($P < 0.001$) effect on the results of SPAD values. A moderately strong correlation was observed between the relative chlorophyll content measured in the V6 phenophase and the yield in the years 2020 (0.313), 2021 (0.492**) and 2023 (0.335*). Furthermore, a statistically significant positive close relationship was found between the ear, grain and cob weight values and the SPAD values measured in the different phenophases in 2020, 2021 and 2022.

In the case of the Normalized Difference Vegetation Index values, it can be said that the weather of the given year affects the development of the values. In 2020 and 2022, the results measured at the 6-leaf stage were the lowest, in 2021 and 2023, all hybrids produced higher results, with the highest result for the H2 (FAO 390-410) genotype in 2023 (0.59). At the 12-leaf stage, the genotypes produced the same values almost every year. The highest measured NDVI value was 0.84 (2020: H2 hybrid, 2023: H3 hybrid). During silking, the hybrids mostly produced lower results, however, in 2020, the H3 hybrid maintained its high NDVI values (0.80). In the physiological maturity stage, the hybrids were more separated from each other. There were evenly high values in 2020 (0.63-0.66), then significantly lower values in the

following years. I obtained a positive close correlation with the yield result with the results measured in the V6 phenophase (0.762***; 0.331*). Based on the results of statistical tests, all the vintage, genotype, phenophase, year x hybrid, year x phenophase, hybrid x phenophase and year x hybrid x phenophase had a significant ($P < 0.001$) effect.

Heat sums:

The earliest germination of the tested hybrids was observed in 2020 (between 05.01.-05.03.). While in 2021 (05.04.-05.06.) and 2022, later germination was typical (05.06.-05.10.). Then in 2023, the germination of the hybrids was also recorded earlier (05.03.-05.05.). In 2020, 2021 and 2023, the sowing date was the same (04.20.), so germination was largely influenced by the weather of the given year.

The effect of the vintage and the difference between the hybrids was also evident in the flowering time. In the extremely drought-prone year of 2022, the earliest male and female flowering of the hybrids occurred. It took 56 and 57 days for the H1 hybrid to reach this state, 55 and 58 days for the H2 hybrid, and 50 and 52 days for the H3 hybrid. Examining the heat sum data, it can be stated that the sums measured in the four years examined show significant differences. The effect of the vintage also appeared in the days required from female flowering to physiological maturity and the associated heat sums, and significant differences can also be observed between the genotypes. The H1 hybrid required 64 days and 721 °C degree days in 2020, while the highest heat requirement from silking to black layer formation was in 2023, 742 °C days (61 days). The H3 hybrid required the least heat to reach physiological maturity in 2023 (1160 °C), while the H2 hybrid required 1348 degree days in 2020.

Yield parameters:

The H2 genotype stood out in the number of grains per cob every year (567-624 pcs). The shortest ear length was measured for all genotypes in 2021 (the shortest H1 hybrid was 16.7 cm). The longest ears were developed by the tested hybrids in 2020 (the longest H2 hybrid was 22.6 cm). In terms of ear diameter, outstanding results can be observed in 2020, with the thickest ear produced by the H2 hybrid (55.5 mm) (Táblázat 2).

Táblázat 2: Result table of yield element parameters in the study of hybrids and years Debrecen-Látókép (2020-2023)

Parameters	Hybrids			
	Years	H1	H2	H3
Thousand grain weight (g)	2020	479,9 ^{ab}	474,4 ^{abc}	436,8 ^{bcd}
	2021	306,1 ^f	370,6 ^e	384,9 ^{de}

Thousand grain weight (g)	2022	395,7 ^{de}	378,1 ^c	486,2 ^{ab}
	2023	421,8 ^{cde}	410,4 ^{de}	523,4 ^a
Grain number (pcs)	2020	493 ^{def}	624 ^a	520 ^{bcd}
	2021	519 ^{bcd}	567 ^{abcd}	495 ^{cdef}
	2022	498 ^{bcd}	585 ^{ab}	453 ^{ef}
	2023	521 ^{bcd}	581 ^{abc}	432 ^f
Ear length (cm)	2020	20,6 ^b	22,6 ^a	20,2 ^{bc}
	2021	16,7 ^c	16,8 ^c	17,5 ^{de}
	2022	19,6 ^{bc}	18,8 ^{bcd}	19,0 ^{bcd}
	2023	18,6 ^{cde}	19,9 ^{bc}	19,5 ^{bc}
Ear diameter (mm)	2020	51,0 ^g	55,5 ^g	49,0 ^g
	2021	45,2 ^f	52,1 ^a	46,4 ^{ef}
	2022	47,3 ^{de}	50,7 ^{abc}	49,0 ^{cd}
	2023	49,1 ^{cd}	51,1 ^{ab}	49,9 ^{bc}
Ear weight (g)	2020	277,9 ^b	358,7 ^a	274,2 ^b
	2021	183,1 ^{cd}	248,2 ^{bc}	216,1 ^{cd}
	2022	216,1 ^d	247,6 ^{bc}	252,3 ^{bc}
	2023	241,1 ^{bc}	264,5 ^b	251,4 ^{bc}
Grain weight (g)	2020	245,4 ^b	307,0 ^a	237,7 ^b
	2021	168,8 ^d	223,4 ^{bc}	195,4 ^{cd}
	2022	197,5 ^{cd}	219,4 ^{bc}	222,0 ^{bc}
	2023	221,2 ^{bc}	237,9 ^b	222,4 ^{bc}
Cob weight (g)	2020	32,48 ^{bc}	51,70 ^a	36,48 ^b
	2021	14,32 ^g	24,74 ^{def}	20,64 ^{efg}
	2022	18,61 ^{fg}	28,18 ^{cd}	30,23 ^{bcd}
	2023	19,97 ^{efg}	26,55 ^{cde}	28,91 ^{cd}
Grain-to-cob ratio (%)	2020	7,6 ^{ef}	6,0 ^g	6,7 ^{fg}
	2021	12,8 ^a	9,1 ^{cde}	9,7 ^{bc}
	2022	10,7 ^b	7,8 ^{def}	7,4 ^{fg}
	2023	11,1 ^b	9,2 ^{cd}	7,9 ^{def}
Number of rows (pcs)	2020	17 ^{abcd}	18 ^{abc}	15 ^{def}
	2021	16 ^{bcd}	18 ^{ab}	14 ^f
	2022	16 ^{cdef}	17 ^{bcd}	16 ^{bcd}
	2023	17 ^{bcd}	19 ^a	15 ^{ef}
Grains per row (pcs)	2020	37 ^{bcd}	42 ^a	40 ^{ab}
	2021	33 ^{de}	32 ^e	39 ^{abc}
	2022	35 ^{cde}	37 ^{bcd}	39 ^{abc}
	2023	37 ^{abcd}	37 ^{abcd}	40 ^{ab}

Different letters for different parameters indicate statistically proven differences between both hybrids and vintages ($p = 5\%$ level).

When examining the ear weight, 2020 can always be considered the best year (274.2-358.7 g). Here too, the H2 hybrid had the highest result (358.7 g). The lowest values were measured in 2021 (H1 hybrid 183.1 grams). This trend remained when examining the grain weight. The grain weight of the H2 hybrid stood out every year. The highest values were achieved in 2020 (307 g). The cob weight values were also the highest in 2020, but the lowest in 2021 (H1 hybrid 14.32 g), with the highest cob weight in 2020, 51.70 g (H2 hybrid). The grain-to-cob ratio was the most favourable in the 2020 experimental year (H2 hybrid 6%) and the highest in 2021 (H1 hybrid 12.8%). In 2023, the tested hybrids achieved the highest average number of grains on the cob (19 pieces), and the lowest values were measured for the H3 hybrid in all four years. The highest number of grains in a row was observed for the H2 hybrid (42 pieces). The lowest thousand-grain weight was achieved by the H1 hybrid (306.1 g) in the 2021 experimental year. The highest thousand-grain weight was measured for the H3 hybrid in 2023 (523.4 g), and for the H1 (479.9 g) and H2 (474.4 g) genotypes in 2020. Looking at the parameters examined, a significant difference can be detected between the hybrids and years in the examination of the hybrids. During the evaluation of the various yield element parameters, I found that both the year and the hybrid ($P<0.001$) and the year x hybrid ($P<0.001$) had a significant effect on the thousand-grain content of the maize hybrids. The development of the grain numbers was significantly influenced by the hybrid ($P<0.001$), and the measured values of the ear length were significantly influenced by the year ($P<0.001$). The development of the ear diameters was significantly influenced by both factors independently and together ($P<0.001$). The year and the hybrid had a significant effect on the development of the ear weight, grain weight, cob weight and grain-to-cob ratio ($P<0.001$). The two factors also had a significant effect on the cob weight ($P<0.05$). During the correlation study, there was a statistically significant positive close relationship between yield and all yield element parameters in each year.

Yield results:

The statement of Gombos and Nagy (2024b) that the year 2020 proved to be almost optimal due to the large amount of precipitation that fell during the growing season and its good temporal distribution is also supported by my own test results, according to which the three genotypes that were present in all four test years achieved outstandingly high yield results (Figure 2).

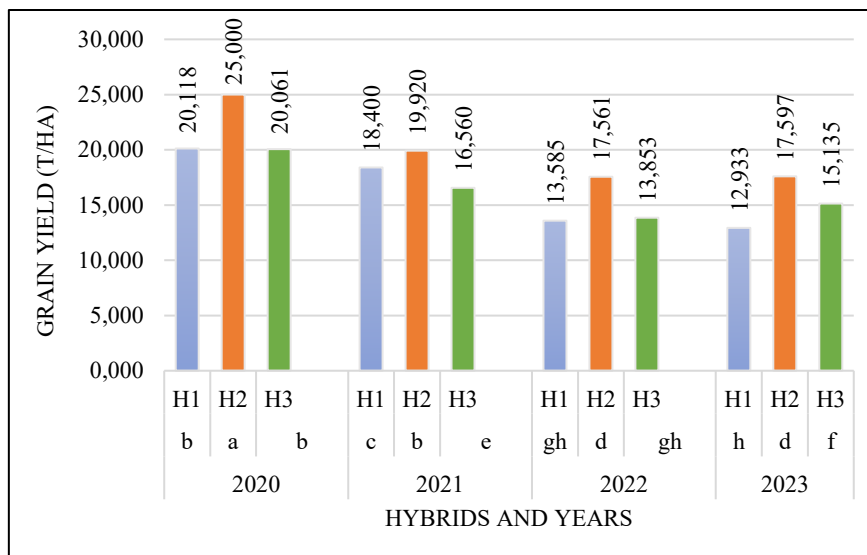


Figure 2: Yield results of maize hybrids between 2020-2023. Debrecen-Látókép. *Different letters indicate statistically proven differences between both hybrids and vintages ($p = 5\%$ level).*

Highlighting the H2 (FAO 390-410) genotype, which reached a yield of $25,000 \text{ t ha}^{-1}$. This year, even the lowest yield exceeded the 18 tons per hectare average (H4- FAO 490). The H2 hybrid also yielded high values in 2021 ($19,920 \text{ t ha}^{-1}$), only the H4 hybrid had a higher yield ($21,600 \text{ t ha}^{-1}$), and the H3 (FAO 350-360) hybrid could be harvested with the lowest yield ($16,560 \text{ t ha}^{-1}$). The record drought year of 2022 was a result of the significantly warm, and mainly in key periods, precipitation-free summer weather, and reduced water resources in the soils, as confirmed by the yield results, with the H2 ($17,561 \text{ t ha}^{-1}$), H3 ($13,583 \text{ t ha}^{-1}$) and H4 ($14,973 \text{ t ha}^{-1}$) hybrids achieving the lowest yield results. In 2023, the moderately warm, balanced temperature conditions and average precipitation of the growing season provided favorable agrometeorological conditions for corn in the Debrecen region, and the yield results also showed an increase compared to 2022, with the exception of the H1 (FAO 420) hybrid with a result of $12,933 \text{ t ha}^{-1}$. The H5 (FAO 490) hybrid also achieved outstanding results ($17,935 \text{ t ha}^{-1}$). Summarizing the yield results of the four years, the most favourable year was 2020 with an average yield of $21,030 \text{ t ha}^{-1}$, followed by 2021 with an average of $19,120 \text{ t ha}^{-1}$, in 2023 the average yield per hectare was 15.900 tons and finally in 2022 the lowest harvestable quantities per hectare ($14,999$ tons). My results can also be statistically verified, according to which, during the examination of the yield parameters of corn, I determined using single and multifactor variance analysis that the yield was significantly ($P < 0.001$) affected by the year, the hybrid and the two factors together. Also, significant differences can be detected between the tested hybrids in the four growing seasons.

Grain composition:

The tested genotypes had the lowest grain moisture content at harvest in 2023, with an average of 14.66%, and the H3 hybrid stood out with 13.9%. The record warm September (20.0 °C) and slightly drier-than-average weather conditions were favourable for grain drying and harvesting operations (Gombos and Nagy, 2024a). Favourable grain moisture content was also observed in 2022 (average: 15.09%). The highest grain moisture at harvest occurred in 2021 (average: 18.39%), while in 2020 the harvested grain also had relatively high moisture (17.88%), which was influenced by the August precipitation levels (Table 3).

Table 3: Results of grain quality parameters by hybrid and year, Debrecen-Látókép (2020-2023)

Parameters	Years	Hybrids		
		H1	H2	H3
Grain moisture (%)	2020	17,0 ^{bc}	17,3 ^{bc}	18,1 ^{ab}
	2021	17,4 ^{bc}	19,2 ^a	16,4 ^{cd}
	2022	15,2 ^{de}	15,0 ^e	14,8 ^e
	2023	14,4 ^e	14,5 ^e	13,9 ^e
Oil content (%)	2020	3,0 ^{cde}	2,7 ^e	3,4 ^{abcd}
	2021	3,2 ^{bcde}	2,9 ^{de}	3,6 ^{ab}
	2022	3,4 ^{abc}	3,3 ^{bcd}	3,8 ^a
	2023	3,8 ^a	3,5 ^{abc}	3,8 ^a
Protein content (%)	2020	6,3 ^{abc}	6,3 ^{abc}	6,1 ^{abc}
	2021	6,2 ^{abc}	6,3 ^{abc}	6,2 ^{abc}
	2022	5,9 ^c	6,7 ^a	6,6 ^{ab}
	2023	5,9 ^{bc}	6,4 ^{abc}	6,6 ^{ab}
Starch content (%)	2020	78,6 ^a	78,7 ^a	78,0 ^a
	2021	78,0 ^a	79,3 ^a	76,1 ^b
	2022	74,8 ^{bcd}	73,8 ^{de}	72,7 ^e
	2023	75,9 ^{bc}	75,7 ^{bc}	74,4 ^{cd}

Different letters for different parameters indicate statistically proven differences between both hybrids and vintages ($p = 5\%$ level).

The highest oil content was measured in 2023 (average: 3.6%). The H2 hybrid consistently had the lowest values each year, staying below 3% in 2020 and 2021 (2.7% and 2.9%, respectively). Higher protein content was measured in the H2 and H3 genotypes in 2022 and 2023 (6.4–6.7%), while lower values were recorded in 2020 and 2021 (6.1–6.3%). The lowest starch content was found in the H3 genotype in 2022 (72.7%), while the highest was recorded for H2 in 2021 (79.3%) and for H4 in 2022 (80.82%). Statistical analysis revealed significant differences among hybrids and years for all tested quality parameters. Grain

moisture content was significantly affected by year ($P<0.001$) and by the year x hybrid interaction ($P<0.005$). Oil and starch contents were significantly influenced by both year and hybrid ($P<0.001$). Across all years, strong or moderate negative correlations were observed between the different quality parameters. Both ecological and genetic factors influence quality traits, leading to substantial differences among genotypes.

Water release:

August and September 2020 were characterized by a moderate ($+1.8^{\circ}\text{C}$, $+1.7^{\circ}\text{C}$) positive temperature anomaly, accelerating the ripening and water release/drying processes (Nagy and Nagy, 2022). In the 2020 study year, the daily rate of water release from the start of measurements (08.25.) to physiological ripening was 1.26% (H1) and 0.87% (H2), in terms of heat sums, 8.13 (H1) and 12.10 (H2) degree days were required for 1% water release. The water loss of the H1 hybrid from physiological ripening to harvest was 0.01% per day, and for the H2 hybrid it was 0.12%.

In September, 19 mm of precipitation fell, thus the drought continued, which created suitable conditions for the water loss and drying of the grain (Gombos and Nagy 2022). In 2021, the daily water loss rate of the H1 genotype was 0.85%, the H2 hybrid 0.92% from the initial date of measurements (07.29.), and 11.89 (H1) and 10.61 (H2) degree days were required for 1% water loss. Its water loss from physiological maturity to harvest was 0.47%/day for the H1 hybrid, 0.41%/day for the H2 genotype.

In September 2022, there was a lot of rain, 152 mm, more than in the previous five months. However, this did not have a positive effect on the corn (Gombos and Nagy, 2023a). In 2022, the rate of water loss (from 07.28) until physiological maturity was 0.69 % (H1) and 0.63 % (H2) per day. During the same period, the H1 hybrid needed 17.81 degree days to lose 1 % of water, and the other hybrid needed 20.68 degree days. Its water loss until harvest was 0.19 %/day for the H1 genotype, and 0.34 % for the H2 hybrid (Table 4).

Table 4: Specific water release and water loss indicators of H1 and H2 hybrids, Debrecen-Látókép (2020-2023)

Years	Specific indicators		H1	H2
2020	Water release From 08.25 to physiological maturity	grain moisture %/day	1,26	0,87
		heat sum $^{\circ}\text{C}$ / 1%	8,13	12,10

	Water loss From physiological maturity to harvest	grain moisture %/day	0,01	0,12
2021	Water release From 07.29 to physiological maturity	grain moisture %/day	0,85	0,92
		heat sum °C/ 1%	11,89	10,61
	Water loss From physiological maturity to harvest	grain moisture %/day	0,47	0,41
2022	Water release From 07.28 to physiological maturity	grain moisture %/day	0,69	0,63
		heat sum °C/ 1%	17,81	20,68
	Water loss From physiological maturity to harvest	grain moisture %/day	0,19	0,34
2023	Water release From 07.31 to physiological maturity	grain moisture %/day	0,91	1,12
		heat sum °C/ 1%	13,20	10,35
	Water loss From physiological maturity to harvest	grain moisture %/day	0,56	0,32

The water loss of the grains and the harvesting work were favoured by the record warm (20.0°C) and slightly drier than average September weather in 2023 (Gombos and Nagy, 2024a). In 2023, from 07.31, the daily water loss of the H1 hybrid was 0.91%, and of the H2 hybrid 1.12%. In terms of heat total, the latter genotype required 10.35 °C/1%, and the H1 hybrid 13.20 °C/1%. Its daily water loss until harvest was 0.56% for the H1 hybrid, and 0.32% for the H2 hybrid.

DSSAT Ceres-Maize simulation results:

For the plant modelling of the DSSAT Ceres-Maize program I used, I chose a multi-nutrient step experiment, the harvested yield of which was compared with the simulated results using a hybrid with excellent genetic properties (FAO 340). In 2016, except for the N0 dose, the model underestimated the yield in all cases. The coefficient of determination of the

measured yield data was $R^2 = 0.88$, and the simulated results were determined with $R^2 = 0.98$. The unit increase in the nitrogen dose was 32.14 kg ha^{-1} for the measured data and 28.68 kg ha^{-1} for the simulated data (Figure 3).

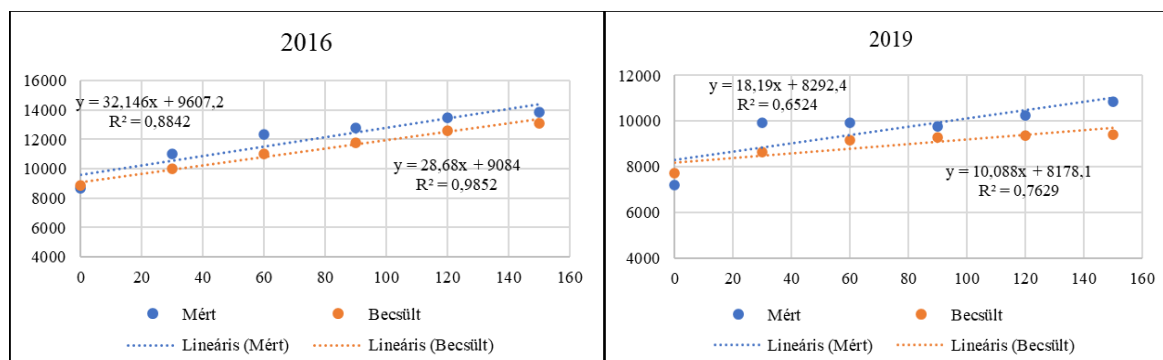


Figure 3: Measured and estimated yield data of the FAO 340 hybrid (2016, 2019)

In 2019, the measured yield results were significantly lower, with the highest yield being 10 t ha^{-1} . The increase in unit nitrogen dose was 18.19 kg ha^{-1} for the measured data, while it was 10.08 kg ha^{-1} for the simulated data. A similar trend can be observed for the simulated yield, but it underestimated it in all cases except for the N_0 dose. I determined the measured results with $R^2 = 0.65$, and the estimated yields with $R^2 = 0.76$.

Based on the experimental results I examined, it can be said that the CERES-Maize model was very sensitive to changes in climatic factors, the model inaccurately simulated maize yield in different N treatments and different growing seasons. In summary, the simulated maize yield was not associated with the site-specific maize yields measured in the experimental plots. A long-term experiment showed that the yield increases with increasing fertilization, which was also followed by the model. The weather of the 5 years examined differed significantly from each other. In the rainy year (2016), the hybrid (FAO340) achieved a yield of $13,858 \text{ kg ha}^{-1}$, while in the drought year (2019) it was 3 tons ($10,860 \text{ kg ha}^{-1}$) less. The estimated results of the model followed the increase in yields with increasing N dose. At each treatment level, the model estimated the yield of the genotype in a similar way, but in several cases the model underestimated or overestimated the yield. In order to predict yields that meet the requirements of precision farming, care must be taken to collect data from experiments conducted under optimal conditions. In addition, the data used for calibration should be collected from a location where detailed soil data are available. The results of the study support the possibility of applying the model to apply appropriate agrotechnics, including the determination of nitrogen dosage. Higher fertilizer doses resulted in higher yields every year (Nyéki et al., 2022b, Zelenák et al., 2021).

4. New scientific results

1. I confirmed and quantified the effects of annual variation on the yield of maize hybrids. In field trials (Debrecen-Látókép), compared to the excellent year 2020, yields were lower by 3.433 t/ha in the average year (2021) and by 6.504–6.726 t/ha in the drought years (2022 and 2023). Despite this, the site's productive potential remained high, with an average yield of 17.560 t/ha over four years.
2. Plant condition assessment based on SPAD (26,8-63,8) and NDVI (0,26-0,86) values accurately reflects the developmental stages and responses to environmental stress of different genotypes of maize hybrids. Year, hybrid, phenophase and their interactions all had significant effects on the development of NDVI values ($P < 0.001$), so these values can be reliable indicators of the adaptability of hybrids.
3. A positive correlation was found between relative chlorophyll content at the V6 stage and final yield in all four years (0,313; 0,492**; 0,335*). In 2020, 2021, and 2023, this relationship was moderately strong and statistically significant ($P < 0.05$), indicating that early chlorophyll measurements can be used to estimate yield potential.
4. In the years studied, I evaluated the parameters of the genotypes and found that plant height and leaf area index were positively correlated with yield. I found a statistically significant ($P < 0.05$), moderately strong positive (0,496**; 0,329*; 0,411**) correlation between both measured phenometric characteristics and yield in three of the four years studied.
5. My studies demonstrated that pre-maturity water release dynamics are genotype-dependent and can be predicted using heat unit-based modelling. For example, in 2020, the H1 hybrid showed faster daily drying (1.26%) than in 2022 (0.69%), but required more heat units per 1% moisture loss in 2022 (17.81 °C) than in 2020 (8.13 °C).
6. I demonstrated that DSSAT CERES-Maize yield forecasts can be validated against experimental data, making the model suitable for predicting hybrid performance under different agrometeorological conditions. The consistency between simulated (6.671-13.136 kg ha⁻¹) and measured yields (5.016-14.920 kg ha⁻¹) supports the model's practical utility in crop management decisions.

5. Practical use of results

1. In all of the years examined, the FAO 390-410 hybrid (H2) with a maturity of 100-100 was the most reliable in terms of grain yield. It achieved a record result in the most favourable year in terms of weather (2021) with a yield of 25,000 t ha⁻¹. Only the FAO 490 (H5 hybrid) produced a nearly identical result in 2023 (17,935 t ha⁻¹). Based on these results, it can be stated that among the hybrids examined, the H2 (FAO 390-410) hybrid can be grown most economically in a similar growing location. Even in the particularly droughty year of 2022, when the weather was unfavourable for corn, its yield (17,567 t ha⁻¹) was the highest.
2. Based on my results, heat unit values provide a more accurate characterization of maize hybrids than growing season length measured in days, which can vary significantly even at the same site from year to year. Classifying hybrids by heat units helps select the most suitable FAO-numbered hybrid for a specific site.
3. Based on research results, the drip irrigation system used during the growing season in drought years is extremely efficient and economical, which was able to mitigate weather-related damage and significantly increase yield in critical phenophases for corn.
4. The water loss capacity of different FAO-numbered hybrids varies. Understanding this in the physiological maturity phase helps optimize harvest timing.
5. Measuring relative chlorophyll content during the growing season helps monitor the health of maize hybrids and can serve as an early indicator of potential yield.

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7. Publications related to the dissertation



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List of publications related to the dissertation

Hungarian scientific articles in Hungarian journals (7)

1. Szanyi, I., Pintér, J., Bojtor, C., Illés, Á., **Zelenák, A.**, Nagy, J.: KWS kukorica (Zea mays L.) hibridek termésparamétereinek összehasonlító értékelése.
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