

Thesis of Doctoral (Ph.D.) Dissertation

**Development and adaptation of millet production technology in
different ecological conditions**

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1. BACKGROUND AND OBJECTIVES OF THE DOCTORAL DISSERTATION

Millet was still cultivated in large quantities in the Middle Ages due to its short growing season, favorable reproduction rate, and relative undemanding. Thanks to its excellent nutritional values, it was an important food for the "poor people", but as time went on, its cultivation fell into the background. Fortunately, along with the expansion of ornamental bird farming and health-preserving, reform diets, millet became increasingly popular again, so this grain could once again become a frequent participant in our diet. In our country, it is mainly known as bird feed and porridge, but it is also used as flour as a raw material for the alcohol industry. In recent decades, it has been cultivated in a small area, mainly as a second crop, in areas released from late surface water in the spring, or used to replace destroyed crops, thanks to its late sowing potential. At the same time, it can be said that nowadays it is becoming more and more popular, and more efforts is being placed on its cultivation and promotion. This is clearly indicated by the fact that the international year of millet became 2023 after 2014.

Millet porridge was often the most important food in the Middle Ages. Currently, it is grown mainly on the African continent, where it is a basic food and the per capita consumption exceeds 100 kg/person/year. The cultivation of the plant - mainly due to its drought tolerance - takes place on the African continent, and among the non-African countries, only the Russian Federation and the USA have a significant area. The area is not only the sowing area of the "proso millet" known in Europe, but the combined sowing area of all known and cultivated millet species (proso millet, pearl millet, foxtail millet and finger millet in the international classification).

The average yield of millet in the world is 900 kg ha^{-1} , which is mainly due to the average yield of African countries with extensive production technologies. Among the countries with the largest sown area, China's average yield stands out, reaching 3 t ha^{-1} . Among the most important millet-producing countries, Ethiopia and India also stand out, where the average yields significantly exceed the world average.

The central place of millet in the domestic food's base was overshadowed by the increasing of corn and the appearance of bread. In our country, at the time of the conquest, the higher social classes, and much later, in the XVII-XIX. century, it was one of the main dishes of the peasantry. The domestic production of millet shows a hectic picture. From the 1960's to the present, the sowing area ranged from 2,000 to 14,000 hectares. The tops of the sown area were in the mid-1960's, the early 1990's, and the early 2000's. In recent years, its sowing area has shown a decreasing trend, currently it is producing on an area of around 2,500 ha.

The average yield of millet shows a similarly hectic picture, which is primarily the result of the extensive cultivation technology, as a result of which the crop year effect is dominant. The yield averages of the last 50 years varied between 500-2500 kg ha⁻¹, dynamic growth in the yield average only characterized the 1970-80's years.

Nowadays, the importance of millet cultivation in our country is not really significant, in recent years and decades, the area of millet production has decreased significantly. Cultivation technology became schematic in many cases, and the adaptivity of the plant was in many cases primary over technological efficiency. This property of millet made it possible to sow late, to grow in unfavorable soil and ecological conditions, so the plant was often classified as "undemanding". However, this is a wrong approach, although millet's reactions to cultivation technology elements are moderate, knowledge of these reactions is necessary for effective cultivation.

Our aims in the studies was to compare the agrotechnical reactions of domestic millet (*Panicum miliaceum*) genotypes under different agroecological conditions. Among the investigated variables, the sowing time, nutrient supply, and the applied sowing technology have a great influence on the yield and agronomic parameters of millet. The research work for my Ph.D. thesis was carried out in the experimental areas of the University of Debrecen Institutes of Agricultural Researches and Educational Farm's Nyíregyháza Research Institute, as well as the Karcag Research Institute, in the period 2013-2016 support and professional guidance of Prof. Dr. Mihály Sárvári.

During our research, we had the following objectives:

- quantification of environment x genotype interactions (G x E) in the case of millet under different ecological conditions
- Effect of different NPK fertilization on yield of millet genotypes, optimization of nutrient supply
- Among the sowing technological parameters, the study of the effect of row spacing in the case of different millet genotypes
- Quantification of the relationship between normal, delayed and late sowing times and the yield and agronomic parameters in the case of millet.

MATERIAL AND METHOD

The experiments were set up in the Nyíregyháza Research Institute of UD IAREF between 2013-2016, and in the Karcag Research Institute of UD IAREF in 2014-2015 (*Picture 1*).



Picture 1. The polyfactorial millet experiment on sandy soil (Nyíregyháza, 2015)

The soil of the Nyíregyháza Research Institute is humic sand soil, according to the WRB classification it can be classified as Arenosols. The soil of the area is characterized by low cohesion ($KA=28$), acidic character and poor water holding capacity. Due to the unfavorable mechanical composition, leaching is strong, and the macro- and micro-nutrient content of the soils is low generally. Its water and nutrient management is more favorable than typical sandy soil, and its clay content is higher. The absorbable nitrogen content is low. The humus content of the soil is around 1%. Based on the results of the sample, the phosphorus supply is excellent, while the potassium supply is average. Based on its physical characteristics and clay content, the soil can be cultivated easily, and no negative conditions affecting the experiment.

The soil of the experiment set up on the meadow soil, in the area of the Karcagi Research Institute, according to the classic soil classification, it can be classified as meadow chernozem type. According to the WRB soil classification, the soil can be classified as Vertisol. The physical type characteristic of the soil is clayly loam, its consistency category is hard ($KA=51$), and it can be evaluated as weakly acidic from the point of view of acidity (pH_{KCl} : 6.59). Its

humus content is high, around 3%. Based on this, the humus content of the soil is good, similar to the K-supply, the P-supply is medium, while the absorbable N-supply is weak-medium. The soil is deficient in Zn, while the supply can be considered adequate for the other tested nutrients. Based on its physical characteristics, the soil can be properly cultivated.

During the analysis of the weather of the experimental years, the long-term average shows the average of the 30 years before to the first experimental year (2013) in the case of tests in Nyíregyháza, in the case of tests in Karcag, the same period is 10 years (2004-2013). The source of the data used in the analysis was the μ Metos by Pessl[®] type meteorological station in both the Nyíregyháza and Karcag Research Institutes.

The rainfall conditions of 2013 were favorable in the first half of the year, however, the rainfall in the months of July and August was significantly below the 30-year average, while September had an average rainfall. This water supply resulted in strong early development in the case of the studied millet genotype, the drier summer period only slightly affected the yield. The temperature trend did not deviate from the long-term average in any extreme way, but at the same time, the temperature of the summer period was warmer than the average.

The weather in 2014 was characterized by extreme heat, the annual average temperature was 12.1 °C, which was the warmest year up to that time based on the measurement data available since 1931. This is primarily due to the extremely high temperatures during the winter semester. The average for the years 1883-2013 was 10.2 °C, in contrast, the average temperature of 2014 was 12.1 °C, which is a significant increase of 1.9 °C. The distribution of precipitation also showed a hectic picture, although the annual precipitation amount (539 mm) did not differ significantly from the 30-year average (549 mm), but at the same time, its distribution within the growing season was extremely uneven. The month of March was characterized by the greatest extremity, when extreme heat was combined with a large lack of precipitation. In terms of precipitation, July proved to be the most extreme, the amount of precipitation was about three times the monthly average for many years. Overall, thanks to the good adaptability of millet, this year can be classified as favorable in terms of yields.

In the area of the Karcag Research Institute, the course of the temperature curve showed a similar picture as in the case of the values measured in Nyíregyháza. The decrease in precipitation was hectic, similar to the results in Nyíregyháza, but we did not experience an amount significantly below the average (below 20 mm) at this location. In contrast to this, the precipitation conditions of the summer-early autumn period differed greatly from the average, in July, September and October, more than twice the monthly average for many years fell.

Overall, it can be said that the temperature and water supply conditions at the site of the experiment were favorable for millet.

The water supply in 2015 was already less favorable in the experimental area in Nyíregyháza. The monthly precipitation averages for the period from February to September did not reach the long-term average, this decrease was mainly typical of the summer months. From the point of view of millet, the average precipitation in May was favorable, which supports the uniform initial development of the plants. The lack of precipitation in the summer period was accompanied by heat, creating a drought situation. The average amount of precipitation in the growing season is 293.2 mm, but in this growing season, about half of the average amount, 165.3 mm, fell. The rainy weather in October made it difficult to harvest of millet, but at the same time, despite millet's good adaptivity, the crop year can be considered unfavorable.

In Karcag, the precipitation during the growing season was similar to the experimental area in Nyíregyháza. The amount of precipitation in the February-July period was far below the 10-year average, creating a drought situation. The precipitation in August was average, but this amount did not have a significant modifying effect on the amount of the crop. The course of the temperature was similar to that experienced at the Nyíregyháza, the average temperature of the July-August period was higher than the average for many years.

In 2016, the water supply in the Nyíregyháza area was particularly favorable during the millet growing season. Although April was particularly dry, in the rest of the growing season there was no lack of rainfall that negatively affected the plant's development. The development of the temperature did not show any particular extremes during the growing period, but the average temperature of the period was higher, but not to an outstanding. Overall, we registered favorable meteorological conditions for millet in this growing year.

The experiment included *Biserka* in 2013, *Biserka*, *Rumenka*, *Maxi*, and *Lovászpatonai* domestic millet varieties between 2014-2016.

In the series of experiments between 2013 and 2016, we examined the agronomic response of millet genotypes under different agroecological and cultivation technology conditions. The experiments were placed according to a uniform methodology, in 4 repetitions per treatment, in a block layout based on three sowing times. In all cases, the forecrop was cereals. The size of the plot was uniformly 1.7 x 9.2 m. During the sowing of the experiments, a uniform seed rate of 8 million germs ha⁻¹ was applied, regardless of different row spacing (12, 24 or 36 cm). The fertilizer active ingredients (control, N₄₀P₄₈K₄₈, N₈₀P₇₂K₇₂, N₁₂₀P₉₆K₉₆ kg ha⁻¹) were applied using Genezis NPK 8-24-24 and Genezis Pétisó 24-0-0. Fertilizers were applied

manually. The harvest date was determined by the grain moisture content of the seeds of the latest sowing period ($14\pm 1\%$), the results are standardized to 14% moisture content.

The NDVI values were recorded with a Trimble GreenSeekerTM hand-held instrument. The time of the measurements was the same within the time of day. The device was used at a height of 50 cm above the leaf surface, with continuous measurement.

The results were processed using the Microsoft Excel[®] program. For statistical evaluation we used SPSS for Windows[®] ver. 22 program. Due to the large number of variables during the statistical evaluation, among the factors, variety was used as the main variable. The normal distribution of the data was tested using the Kolmogorov-Smirnov test. The significance of the differences between groups was established using the Tukey test. Correlation studies between the results were evaluated using Pearson's correlation analysis. The influencing factors were weighted by dividing variance components. The figures were created using the Microsoft Excel[®] program.

2. RESULTS AND DISCUSSION

2.1. Evaluation of NDVI values in the millet polyfactorial experiment

During the vegetation period of two years (2015, 2016), the measurements were carried out 3 and 4 times in the experiment. One of the defining differences between the two crop years was that we measured lower values in the drought year in 2015 due to earlier drying of the vegetation. The evaluation of the NDVI values was not consistent with the effect of the sowing times in 2015, despite the fact that we experienced a significant difference between the effects of the sowing times in the case of the *Rumenka* and *Biserka* varieties. In 2016, measurements during the flowering period (29.07 and 08.08) confirmed the more favorable values of the later sowing times, which is mainly due to differences in the phenological stages. In the late sowing time, however, we experienced a significantly lower NDVI values at the last measurement time, which indicates the unfavorable effect of late sowing (*Figure 1*). In the case of the *Lovászpatonai* millet variety, we obtained higher NDVI values compared to the previous two varieties, which is due to the plant's different habitus, number of leaves and height. The effect of sowing time was slightly more consistent in 2015 compared to the previous varieties, we registered a significantly higher NDVI values at the two later measurement times. This trend can also be observed in 2016, in the case of the last three measurements, we experienced a significantly higher NDVI values in the case of late sowing, which suggests the stronger vegetative property of the variety.

In the case of the *Maxi* millet variety, the effect of sowing time was not clear in 2015, even though we found significant differences between the NDVI values for different sowing times. At the same time, similarly to what was experienced in the case of the *Lovászpatonai* variety, in 2016, at the three later measurement times, we measured the more favorable values clearly and statistically at the delayed sowing time.

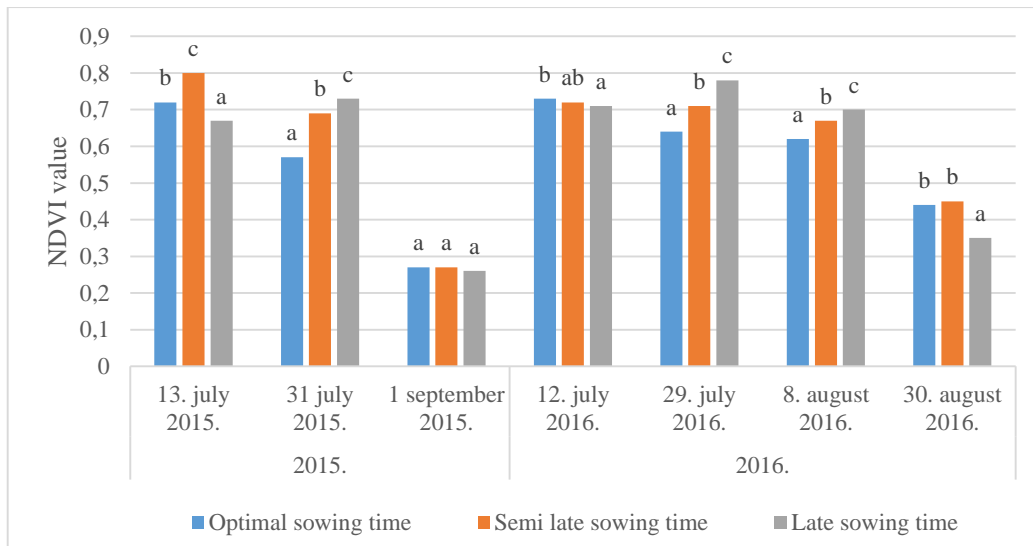


Figure 1. Evaluation of the NDVI values of the *Rumenka* millet variety in different years with different sowing times in the average of fertilizer treatments and row spacings (Nyíregyháza)

In the drought year of 2015, the effect of increasing fertilizer doses was not consistent, but at each measurement time, we measured the lowest NDVI values at the highest fertilizer level, which suggests a depressing effect of fertilization. In contrast to this, in the year 2016 with more favorable weather conditions, the reaction to increasing fertilizer doses was consistent in the case of the *Rumenka* and *Biserka* varieties, the highest NDVI values were measured at the highest fertilizer level at each measurement time, and the NDVI values also increased as a result of increasing fertilizer doses.

The effect of the fertilizer treatments was consistent in the dry season at the highest fertilizer level, at each measurement time we measured the significantly lowest NDVI values for the *Lovászpatonai* variety. In contrast to this, in the more favorable 2016 cropyear, we measured the most favorable NDVI values at the highest fertilizer level at each measurement time. Together with the increase in the fertilizer levels, the NDVI values also increased at each measurement time, there was a significant difference between the control treatment and the N₁₂₀P₉₆K₉₆ fertilizer level at each measurement time.

The effect of row spacing was the least consistent in the case of varieties, in the drought year (2015) we did not experience any significant differences between the effects of different row spacings, while in 2016 the indicator developed more consistently.

2.2. Millet yield under different agroecological conditions

The yield of millet varied between 2.876-5.973 t ha⁻¹ in the average of the examined variables (nutrient supply, variety) at the two production sites, which is a particularly high yield. In the case of Biserka and Maxi millet, the fertilizer treatments did not result in a significant effect. In the case of the Rumenka millet variety, we experienced a significant yield increase only at the highest fertilization level, on meadow soil. The location x fertilizer interaction was the largest for the Lovászpatonai millet variety, the yield result of the highest fertilizer level on both meadow and sandy soil significantly exceeded the yield in case of other fertilizer treatments, so the most marked location x nutrient supply interaction was observed for this variety (*Figure 2*).

Figure 3 shows the yield differences per location for the tested varieties and nutrient levels, based on the yield results in Nyíregyháza. The yield difference of the control treatments varied between -0.089-0.253 t ha⁻¹, which shows great stability in terms of the yield of the varieties without fertilization. In the NPK 40-48-48 kg ha⁻¹ treatment, only the yield of Biserka variety changed to a large extent (0.973 t ha⁻¹ the difference between the yield results measured at the two production sites), in the case of the other varieties the difference was small (-0.049-0.396 t ha⁻¹). The results of the NPK 80-72-72 kg ha⁻¹ treatment also showed a small deviation (-0.079-0.313 t ha⁻¹), but at the highest fertilizer level the deviation of the values was significant. The extreme values of the yield results were -0.103-1.573 t ha⁻¹, the large positive differences occurred on the meadow soil. Among the tested varieties, the Biserka variety was characterized by the highest standard deviation (2.299 t ha⁻¹), while Maxi millet variety showed the highest yield stability with the highest yield level (0.519 t ha⁻¹). Among the examined genotypes, we could only detect a significant effect of the location of production in the average of the fertilizer treatments in the case of the Rumenka variety in the average of the production sites and the fertilizer treatments.

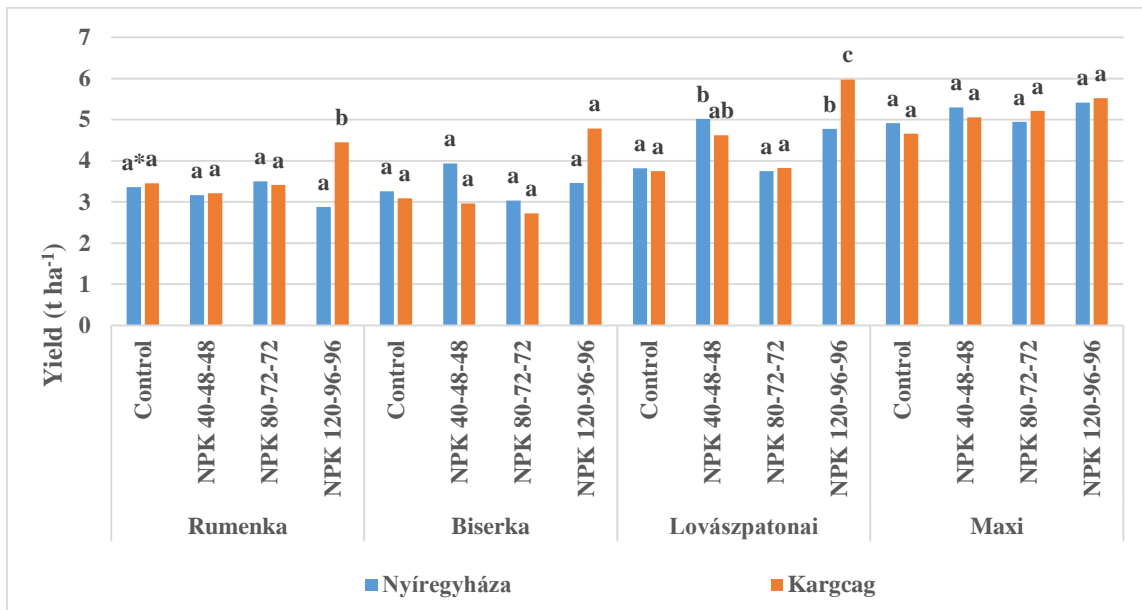


Figure 2. The effect of nutrient supply on the millet yield in different production locations in 2014

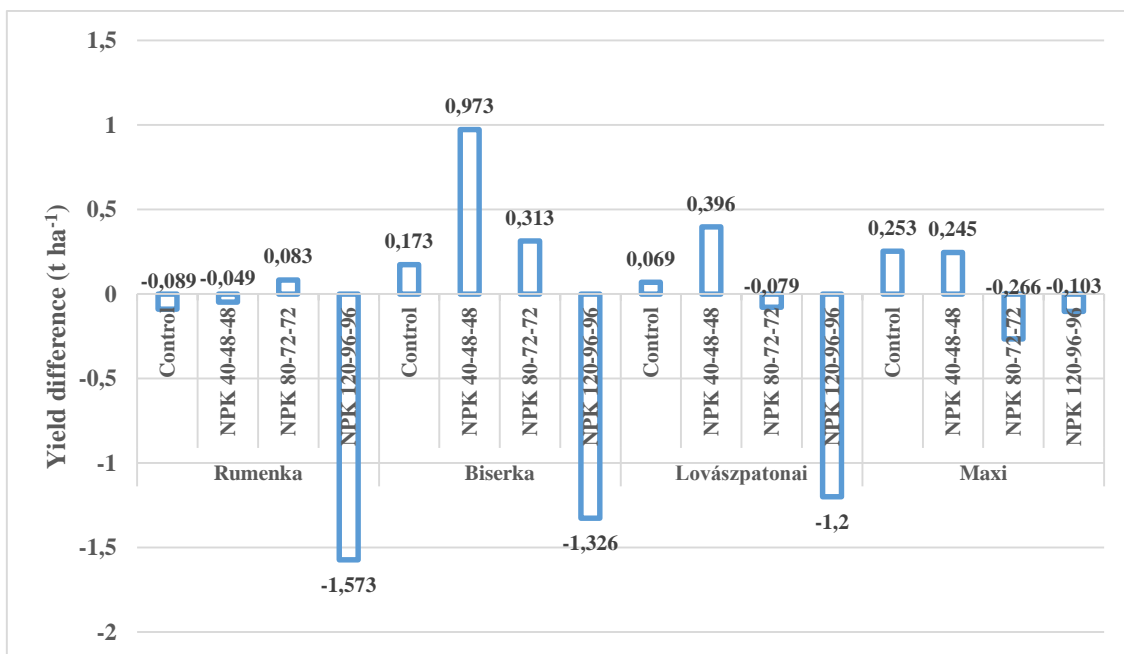


Figure 3. The yield difference between production sites at different levels of nutrient supply for the examined millet genotypes

We found a significant difference between the examined cropyears in the case of the yield of the *Biserka* millet variety. The most favorable year was 2013, where the average yield of the treatments was 4.82 t ha⁻¹. 2015 turned out to be the most unfavorable year, where we harvested an average of 1.18 t ha⁻¹ of the treatments. In 2016, the yield was 1.99 t ha⁻¹, while in 2014 this value was 2.84 t ha⁻¹ (Figure 4).

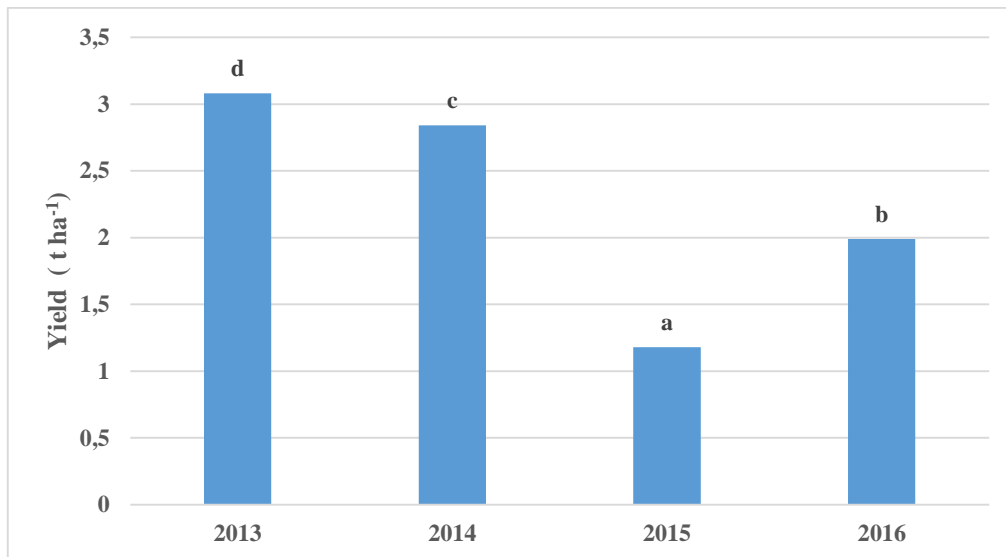


Figure 4. The development of the yield of *Biserka* millet variety in the average of the treatments (row spacing, fertilizer, sowing time) in different years (Nyíregyháza)

Based on the test results of the four examined years, the yield-reducing effect of the late sowing time was statistically confirmed, but the effect of the two earlier sowing times on the yield was not significant (*Figure 5*). In the 4-year average of the treatments, the yield of the earliest sowing time was 2.96 t ha⁻¹, this value was 2.87 t ha⁻¹ in the second sowing time. In the third, late sowing time, the yield was significantly lower (2.29 t ha⁻¹) in the case of *Biserka* variety.

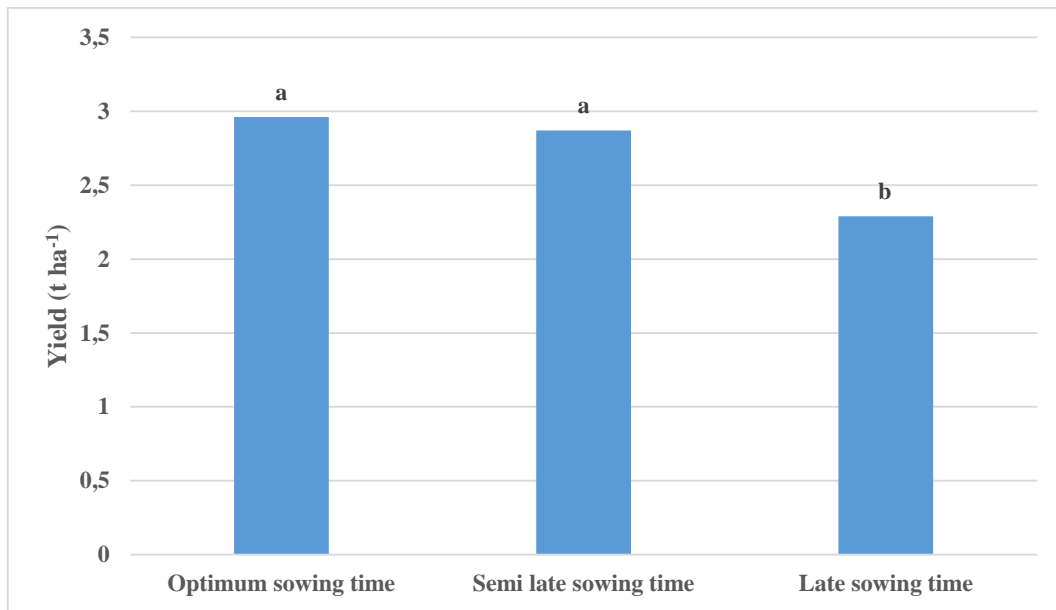


Figure 5. The evaluation of the yield of *Biserka* millet variety in the case of the application of different sowing times in the average of the examined years and treatments (row spacing, fertilizer) (Nyíregyháza)

Changing the row spacing did not result in a significant difference in case of *Biserka* variety (Figure 6). The highest yield was obtained using the row spacing of 24 cm in the average of the treatments (2.83 t ha⁻¹), the smallest yield was obtained using the row spacing of 12 cm (2.55 t ha⁻¹). When the largest row spacing of 36 cm was used, the yield was 2.74 t ha⁻¹ in the average of treatments and years.

Similarly, changing the nutrient strategy did not result in a significant difference in the case of *Biserka* variety (Figure 7). The highest yield was achieved with the application of the NPK 40-48-48 kg ha⁻¹ nutrient supply level in the average of the treatments (2.74 t ha⁻¹), the lowest yield resulted from the application of the NPK 80-72-72 kg ha⁻¹ nutrient supply level (2.68 t ha⁻¹). In the case of the application of the largest, NPK 120-96-96 kg ha⁻¹, the yield was 2.69 t ha⁻¹ in the average of treatments and years.

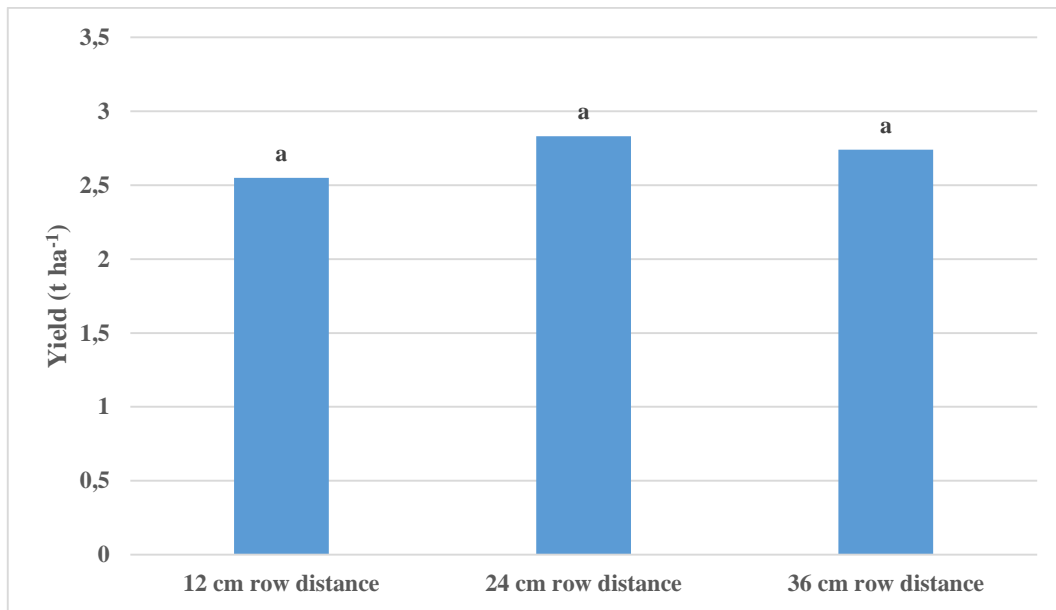


Figure 6. The evaluation of the yield of *Biserka* millet variety when using different row spacings in the average of the examined years and treatments (sowing time, fertilizer) (Nyíregyháza)

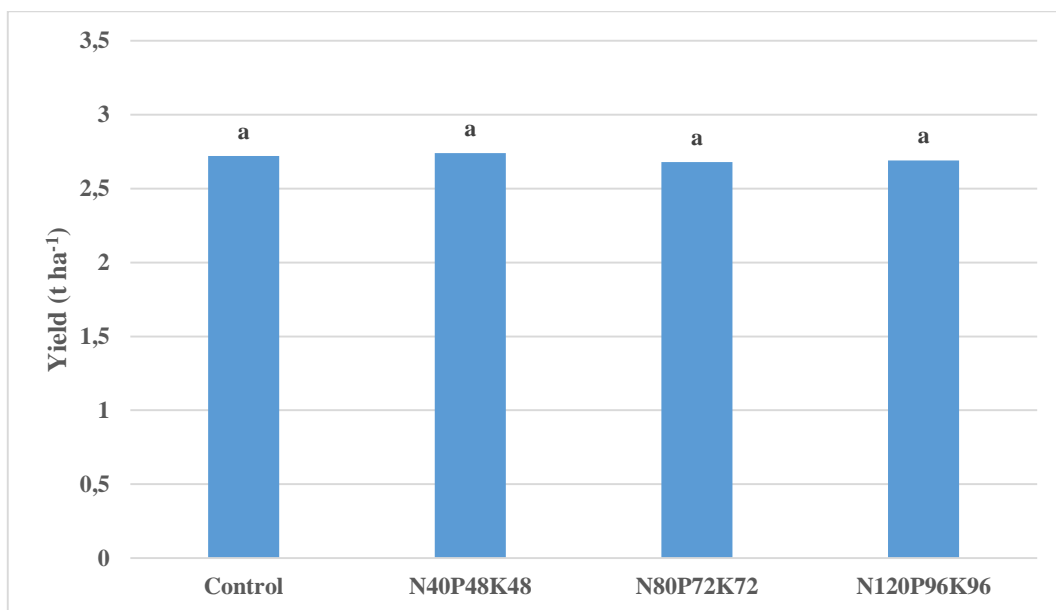


Figure 7. The yield of *Biserka* millet variety at different levels of nutrient supply in the average of the examined years and treatments (sowing time, row spacing) (Nyíregyháza, 2013-2016)

Based on the results of the examined conducted between 2014-2016, among the tested millet genotypes, the yield of the *Maxi* variety was significantly higher (2.57 t ha⁻¹) compared to the other examined varieties (*Figure 8*) in the average of treatments and years. In the case of *Rumenka* (2.06 t ha⁻¹), *Biserka* (2.00 t ha⁻¹) and *Lovászpatonai* (2.08 t ha⁻¹) varieties, the yield was similar, the difference between them was not significant for the treatments and years on average.

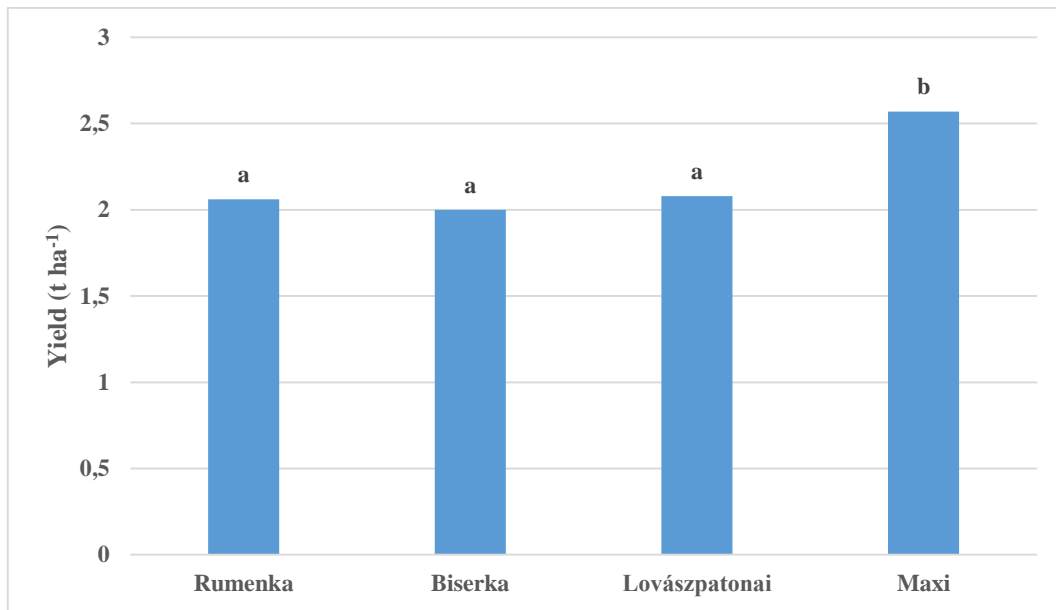


Figure 8. Evaluation of the yield of millet genotypes in the average of the studied years and treatments (sowing time, fertilizer, row spacing) (Nyíregyháza, 2014-2016)

The effect of the examined cropyears was strong in terms of millet yield (*Figure 9*). The most favorable year was 2014, in this year the millet yield was 3.26 t ha⁻¹ on average for treatments and varieties. The lowest yield was measured in 2015 (1.18 t ha⁻¹), the yield in 2016 was 2.10 t ha⁻¹ in the average of treatments and varieties. The difference between years was significant.

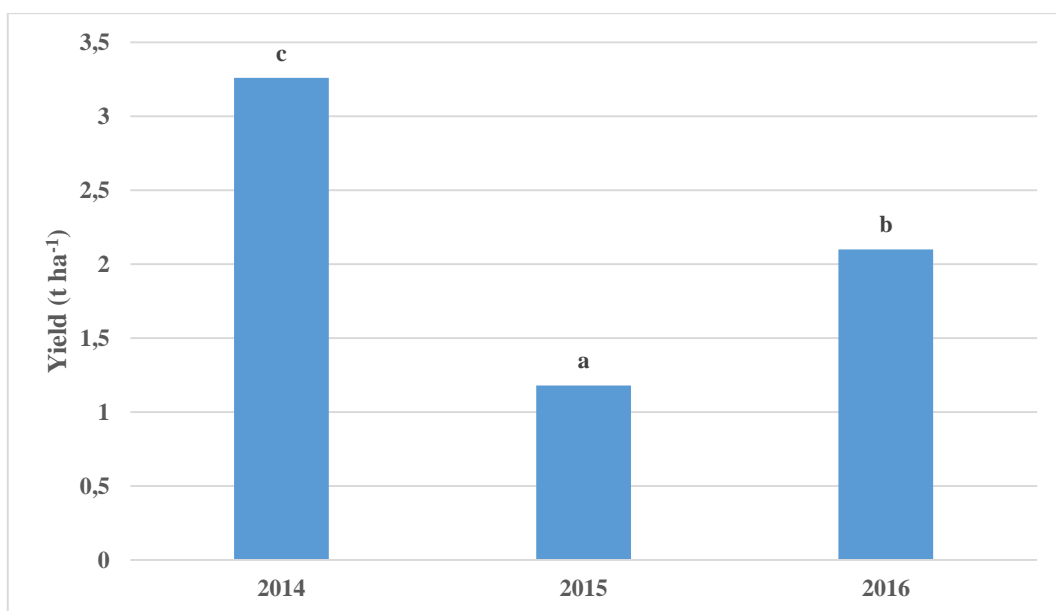


Figure 9. Trends in millet yield in different years in the average of treatments (sowing time, fertilizer, row spacing) and varieties (Nyíregyháza, 2014-2016)

Similar to the results of the experiments with *Biserka* millet variety, in addition to the year, the sowing time also had a clear, significant effect on the yield of the tested millet varieties (Figure 10). The highest yield was obtained when the first, optimal sowing time was used (2.46 t ha⁻¹), this was significantly lower when the delayed sowing time was used (2.25 t ha⁻¹), the lowest yield was obtained when the late sowing time was used (1.83 t ha⁻¹).

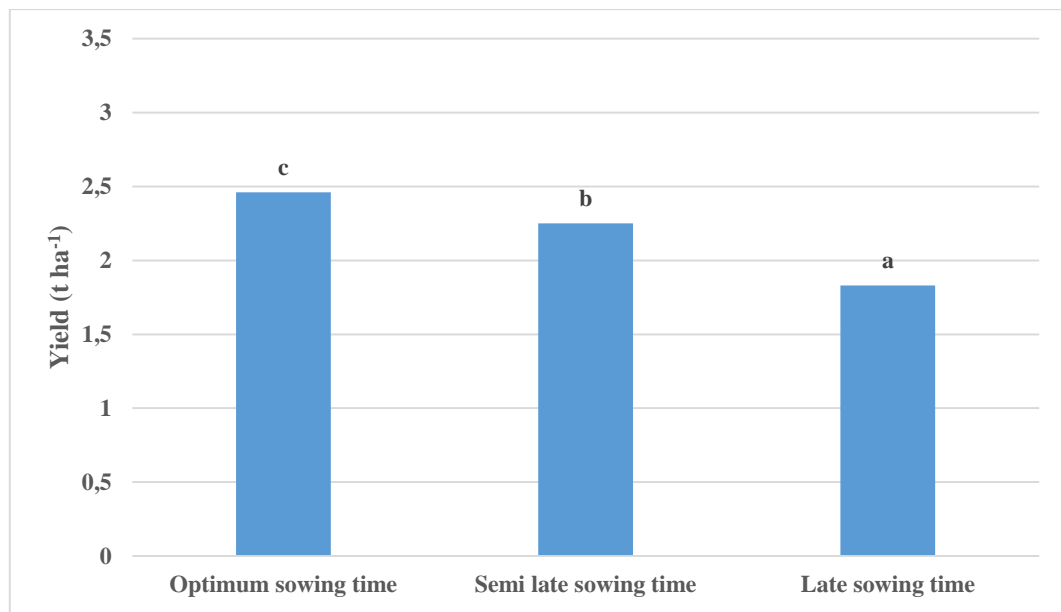


Figure 10. Evaluation of millet yield in the case of different sowing times in the average of the examined years, treatments (fertilizer, row spacing) and varieties (Nyíregyháza, 2014-2016)

Similar to the results of the 4-year experiment with *Biserka* variety, neither the different row spacing nor the different nutrient supply resulted in significant differences in the yields of the four millet varieties examined. In the case of the row spacing (Figure 11), the yields moved in a very narrow interval (2.17-2.19 t ha⁻¹).

The effect of nutrient supply was not significant even in the three-year study (Figure 12). Similar to the effect of row spacing, the values in this case also moved within a narrow interval (2.14-2.25 t ha⁻¹).

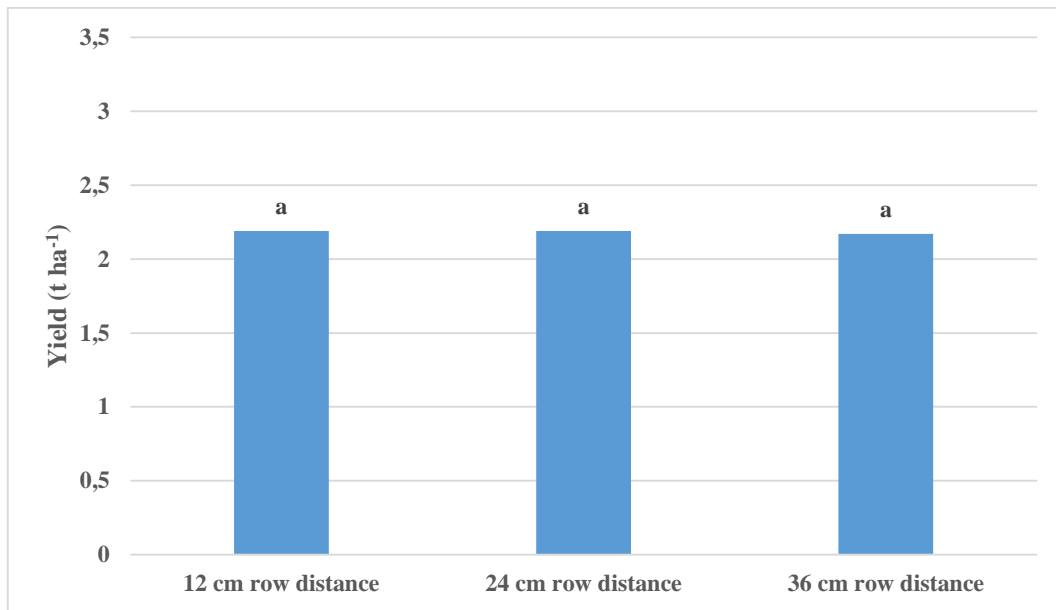


Figure 11. Evaluation of millet yield in the case of application of different row spacings in the average of the investigated years, treatments (fertilizer, sowing time) and varieties (Nyíregyháza, 2014-2016)

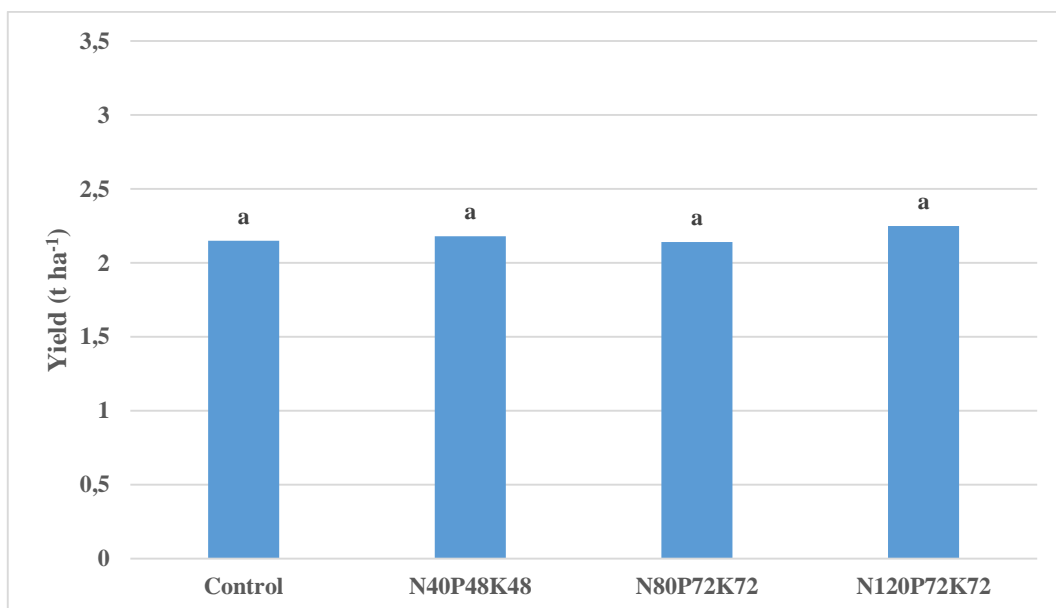


Figure 12. Evaluation of millet yield in the case of application of different nutrient supply levels in the average of the studied years, treatments (row spacing, sowing time) and varieties (Nyíregyháza, 2014-2016)

In the experiment set up in two different ecological regions, the effect of different ecological circumstances and the crop year proved to be significant. Among the studied production locations, the main average of the experiment set up in Nagykunság was significantly higher (4.05 t ha⁻¹) than the yield obtained on the sandy soil of Nyírség (2.64 t ha⁻¹). Among the examined crop years (2014-2015), in the average of the production sites, the year

2014 can be characterized by an order of higher yield (4.11 t ha^{-1}) compared to the year 2015 (1.71 t ha^{-1}).

The significant yield surplus of the *Maxi* millet variety (Figure 13) was also valid in the average of the tests in two different production locations in the two years (3.94 t ha^{-1}), in the case of *Biserka*, *Rumenka* and *Lovászpatonai* varieties, the yield difference was not significant (2.70 , 2.81 and 3.27 t ha^{-1} , respectively).

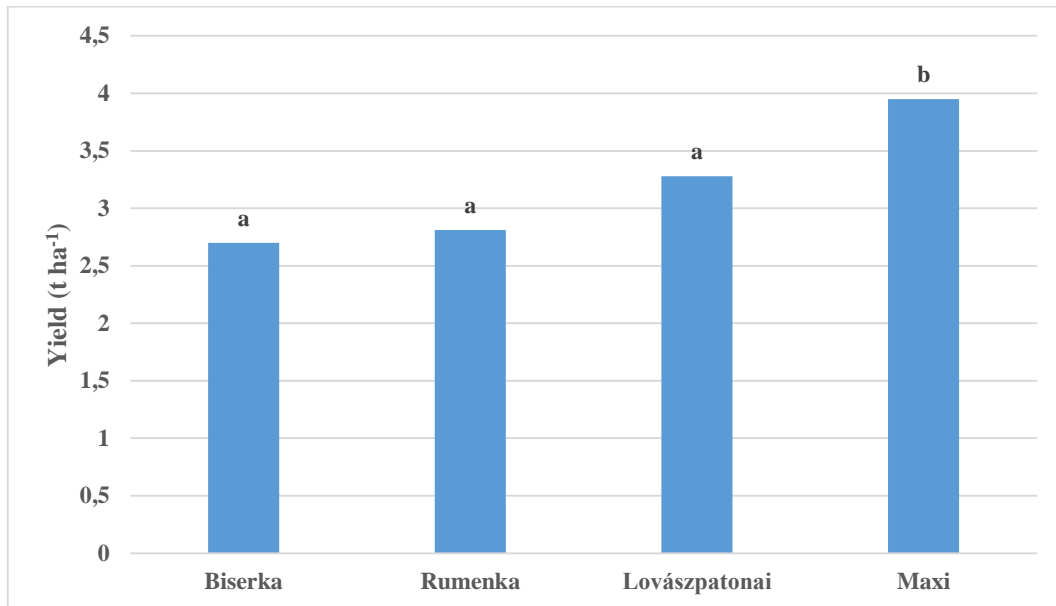


Figure 13. Evolution of the yield of millet genotypes in the average of the yields of two cropyears

2. 3. Assessment of the impact of environmental elements affecting yield using Pearson's correlation analysis

In the assessment of the impact of weather factors, on the basis of the tests carried out based on the results of the previous three years - according to which neither fertilization nor the variable row spacing had a significant effect on the development of the amount of the crop - we examined the variety and sowing time groups during the correlation analysis. We correlated the weather parameters with the amount of the crop and evaluated them by variety and sowing time. During the evaluation, 30 (HUDAS₃₀), 30-60. day (HUDAS₆₀), 60-90 day (HUDAS₉₀), 90-120. day (HUDAS₁₂₀) and the effective heat unit of the total growing season (HU_{total}) were determined. In the first 30-day period of the development stage, only the *Rumenka* and *Maxi* millet varieties experienced a strong, positive correlation with the amount of effective heat units, in the case of both varieties when the earliest sowing time was used. The amount of heat

units in the period 30-60 days after sowing did not show a close correlation with the yield of either variety or sowing time, while the 61-90 days after sowing showed no close correlation. The effective heat units of days showed a close, negative correlation in the case of *Rumenka*, *Lovászpatonai* and *Maxi* millet varieties in the delayed sowing time. The effective heat units of the last quarter of the growing season (days 91-120) showed a negative correlation in all cases, in the case of *Lovászpatonai* and *Maxi* millet varieties in all three sowing times, in the case of *Rumenka* in the first two sowing times, while in the case of *Biserka* only in the 2nd sowing time. Without exception, the amount of effective heat units during the growing season showed a negative correlation with the yield for all tested varieties and sowing times (*Table 1*).

Table 1. Examination of the effect of effective heat units on yield using Pearson's correlation analysis
(Nyíregyháza, 2014-2016)

Variety	Sowing time	HUDAS ₃₀	HUDAS ₆₀	HUDAS ₉₀	HUDAS ₁₂₀	HU _{total}
<i>Biserka</i>	1. sowing time	,527**	-,686**	,545**	-,620**	-,571**
	2. sowing time	-,301**	,167*	-,519**	-,842**	-,663**
	3. sowing time	,535**	-,676**	-,665**	-,365**	-,588**
<i>Rumenka</i>	1. sowing time	,844**	-,434**	,227**	-,898**	-,871**
	2. sowing time	-,217**	,078	-,600**	-,886**	-,732**
	3. sowing time	,471**	-,658**	-,847**	-,558**	-,778**
<i>Lovászpatonai</i>	1. sowing time	,741**	-,551**	,364**	-,812**	-,776**
	2. sowing time	-,375**	,238**	-,485**	-,848**	-,643**
	3. sowing time	-,252**	,032	-,874**	-,905**	-,903**
<i>Maxi</i>	1. sowing time	,801**	-,540**	,340**	-,870**	-,835**
	2. sowing time	-,431**	,297**	-,436**	-,823**	-,602**
	3. sowing time	-,146	-,085	-,937**	-,915**	-,951**

*correlation is significant at 5%

**correlation significant at 1%

With regard to precipitation, we determined the examined periods on the basis of a similar methodology, and correlated the precipitation amounts of 30-day intervals (PDAS) with the yield results per sowing time and per variety in the average of row spacing and fertilizer treatments (*Table 2*). The amount of precipitation in the first 30-day interval shows a weak, negative correlation in the first two sowing times, while in the third, latest sowing time, the

direction of the correlation is positive, in the case of *Lovászpatonai* and *Maxi* varieties, we experienced a particularly high correlation value ($r^2 = 0.839$ and 0.817 , respectively). The amount of precipitation was primarily dominant between days 31-90 of the growing season, except for the latest sowing time of *Biserka* and *Rumenka* varieties. The amount of precipitation in 91-120 days after sowing also had a consistent effect, in the case of all varieties we experienced a particularly strong, positive correlation at the earliest sowing time ($r^2 = 0.863$ - 0.936). The amount of total precipitation during the growing season also showed a similar trend, with the exception of the *Biserka* variety, we experienced a strong positive correlation with the yield in the earliest sowing time, while in the case of the *Lovászpatonai* and *Maxi* millet varieties, we also experienced a strong positive correlation in the latest sowing time ($r^2 = 0.914$ - 0.934).

Table 2. Examination of the effect of the amount of rainfall during the growing season on the yield using Pearson's correlation analysis
(Nyíregyháza, 2014-2016)

Variety	Sowing time	PDAS ₃₀	PDAS ₆₀	PDAS ₉₀	PDAS ₁₂₀	PDAS _{total}
<i>Biserka</i>	1. sowing time	-,529**	,722**	,854**	,863**	,620**
	2. sowing time	-,230**	,883**	,848**	,552**	,706**
	3. sowing time	,158	,432**	,385**	-,068	,425**
<i>Rumenka</i>	1. sowing time	-,206*	,940**	,913**	,886**	,898**
	2. sowing time	-,143	,917**	,891**	,484**	,771**
	3. sowing time	,340**	,627**	,579**	-,242**	,620**
<i>Lovászpatonai</i>	1. sowing time	-,345**	,880**	,918**	,905**	,812**
	2. sowing time	-,303**	,899**	,855**	,627**	,691**
	3. sowing time	,839**	,915**	,909**	-,794**	,914**
<i>Maxi</i>	1. sowing time	-,319**	,934**	,954**	,936**	,870**
	2. sowing time	-,360**	,882**	,831**	,674**	,653**
	3. sowing time	,817**	,936**	,922**	-,760**	,934**

*correlation is significant at 5%

**correlation significant at 1%

The indicator of precipitation efficiency is the amount of yield per 1 mm of precipitation, the evaluation of which is shown in Table 3 per sowing period in the years under study. During the calculation, we used the amount of precipitation during the first 120 days of the growing

season as a basis. The value of precipitation efficiency was the lowest in the late sowing time, with the exception of 2016. Among the examined years, the narrowest interval was obtained in 2016 (6.62-14.31 kg mm⁻¹ ha⁻¹), the largest standard deviation was obtained in the driest year, 2015 (4.40-18.52 kg mm⁻¹ ha⁻¹). Among the examined varieties, extreme values of 4.40-14.31 kg mm⁻¹ ha⁻¹ were observed in the case of *Rumenka* millet, and similar values were obtained in the case of *Biserka* and *Lovászpatonai* varieties (5.67-17.11 and 5.14-15.45 kg mm⁻¹ ha⁻¹), the most favorable values were observed for *Maxi* millet variety (5.74-19.51 kg mm⁻¹ ha⁻¹). This trend also prevailed in the average of years and sowing times.

Table 3. Evaluation of rainfall efficiency (kg mm⁻¹ ha⁻¹) for different genotypes in different years and different sowing times (Nyíregyháza, 2014-2016)

		<i>Rumenka</i>	<i>Biserka</i>	<i>Lovászpatonai</i>	<i>Maxi</i>	Average
2014	1. sowing time	12,98 ^b	12,97 ^b	14,43 ^c	16,04 ^c	14,11
	2. sowing time	13,05 ^b	13,28 ^b	13,54 ^b	19,51 ^b	14,85
	3. sowing time	7,67 ^a	6,57 ^a	10,01 ^a	5,74 ^a	7,50
2015	1. sowing time	14,63 ^c	17,11 ^c	12,58 ^b	16,74 ^b	15,27
	2. sowing time	10,75 ^b	11,74 ^b	15,45 ^c	18,52 ^c	14,12
	3. sowing time	4,40 ^a	5,67 ^a	5,14 ^a	11,13 ^a	6,59
2016	1. sowing time	10,45 ^b	7,60 ^b	9,02 ^b	12,18 ^b	9,81
	2. sowing time	7,21 ^a	6,62 ^a	7,45 ^a	8,63 ^a	7,48
	3. sowing time	14,31 ^c	14,01 ^c	9,20 ^b	11,39 ^b	12,23
Average		10,61	10,62	10,76	13,32	11,33

2.4. Analysis the effect of factors affecting millet yield by dividing the variance components

The division of the variance components was carried out based on the results of the experiments carried out in Nyíregyháza. The results of the 4 tested varieties between 2014-2016 were included in the analysis. The cropyear had the greatest effect on the millet yield, which also indicates the unfavorable effect of climate change, the weather conditions of the examined period were dominant. Among the examined technological factors, the effect of sowing time proved to be the largest (16%), while the effect of the variety was 14%. The effect of the nutrient supply was 2%, while the effect of the applied row spacing was negligible (*Figure 14*).

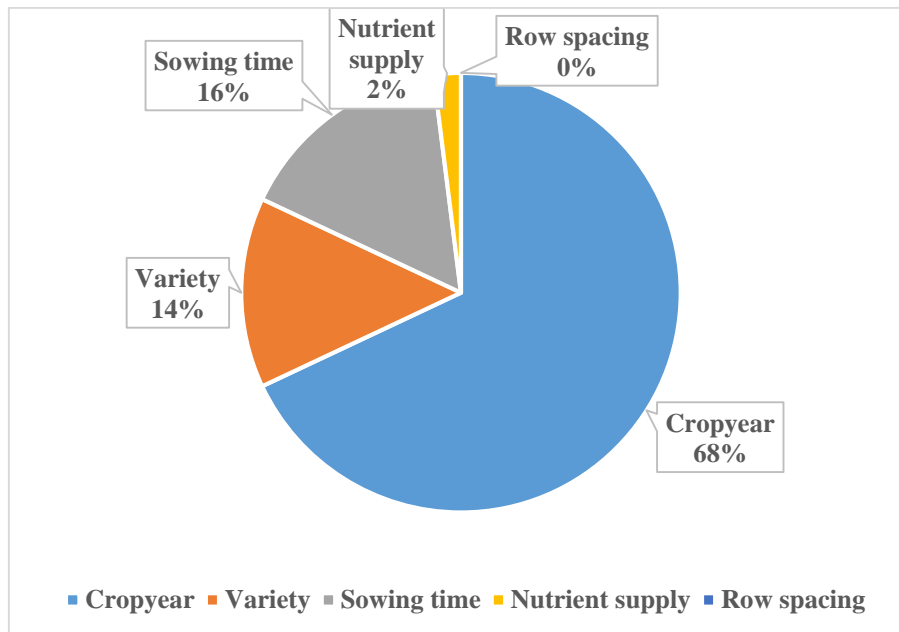


Figure 14. The role of the crop year and the examined technological elements on the millet yield
(Nyíregyháza, 2014-2016)

If only the effect of technological elements is examined, the role of sowing time and variety was dominant (*Figure 15*). The sowing time determined the development of the crop in 49 %, which somewhat contradicts the image formed in the cultivation practice of millet, according to which it is a plant with a plastic sowing time. The role of nutrient supply was small (7%), while the effect of the applied row spacing was not significant in this case either.

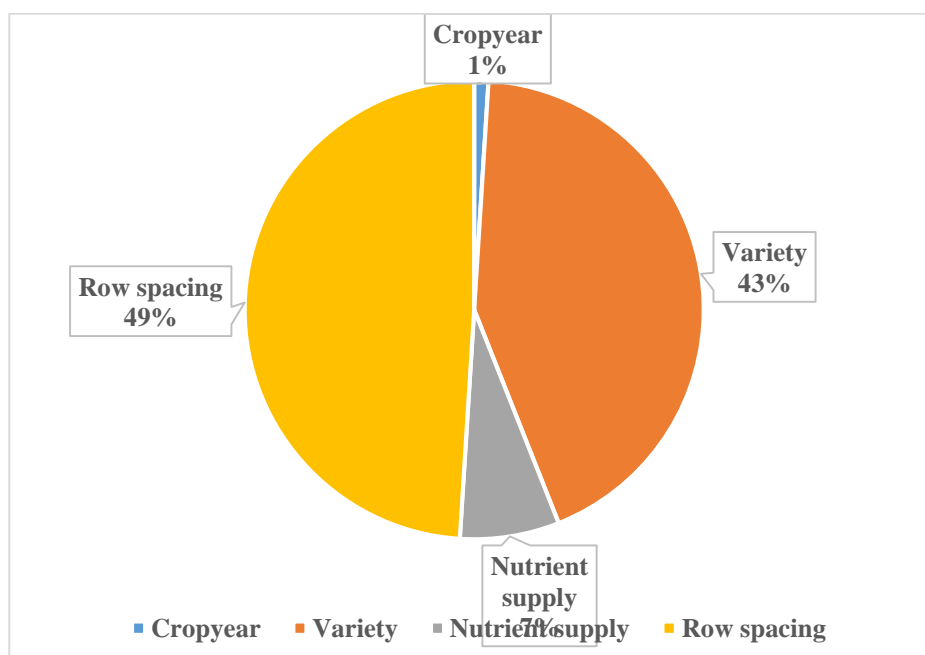


Figure 15. The role of the crop year and the examined cultivation technology elements in the development of the millet yield

3. NEW SCIENTIFIC RESULTS

1. Warming and lack of rainfall as a result of climate change modify the classic interpretation of millet cultivation (late sowing, sowing in areas with surface water, second crop), based on our investigations, the late sowing time significantly reduced the yield of millet varieties (in case of sown in the second decade of May, 2.46 t ha⁻¹, 2.25 t ha⁻¹ in sowing at the end of May, while 1.83 t ha⁻¹ in the case of sowing in the middle of June).
2. The positive correlation between the NDVI values and the yield could only be verified in the more favorable crop year and later sowing times in the case of *Rumenka*, *Biserka* and *Lovászpatonai* millet varieties. Based on these, forecasting the crop based on NDVI values is not recommended in the case of millet.
3. The yield change caused by the year resulted in significant extreme values due to climate change (0.11-5.94 t ha⁻¹), so in case of millet, the adaptive capacity must also be re-evaluated according to based on the previously published Hungarian test results.
4. Among the tested varieties, the *Maxi* variety stood out, the yield of which significantly exceeded the yield of the other three tested varieties (*Rumenka*, *Biserka* and *Lovászpatonai*) in both tested production locations in each year and in the average of the treatments, so the ecological plasticity of the variety was the highest among the tested varieties.
5. Neither the nutrient treatments nor the row spacing proved to be significant in the case of millet, so the reactions to the technological inputs were moderate in the case of the species.
6. Pearson's correlation tests showed a negative correlation between the temperature of the growing season and the yield for all sowing times ($r^2 = -0.365 - -0.915$ r^2 values). In the case of *Maxi* millet variety with the highest productivity, these values showed a significant negative correlation in the delayed sowing time ($r^2 = -0.915 - -0.951$), which, in addition to the high yield potential of the variety, draws attention to the risk of late sowing in the case of the variety.
7. The effect of precipitation on yield was clear for all varieties. The amount of precipitation in the period of 30-60 days of the growing season ($r^2 = 0.432 - 0.940$) and the amount of precipitation in the period of 60-90 days ($r^2 = 0.385 - 0.954$) showed a close positive correlation with the yield, in the case of the *Lovászpatonai* and *Maxi* millet varieties, there was a close positive correlation in all three sowing times ($r^2 = 0.880 - 0.954$).
8. The water use efficiency showed significant genotype dependence, the highest values were observed in the case of *Maxi* millet (5.74 – 19.51 kg ha⁻¹ mm⁻¹, the average of the years and

treatments was $13.32 \text{ kg ha}^{-1} \text{ mm}^{-1}$), similar values were observed for the other three examined varieties ($10.61 - 10.76 \text{ kg ha}^{-1} \text{ mm}^{-1}$ on average for the treatments).

4. RESULTS THAT CAN BE USED IN PRACTICE

1. The impact of climate change in recent decades, but especially in recent years, has resulted in a significant variance in terms of yield in our tests, even in the case of millet, which was previously considered undemanding and drought-tolerant, **which indicates the greater sensitivity of the plant to changed environmental conditions.**
2. The results of the correlation studies of **NDVI values** with yield did not show a clear correlation, so the application of yield in forecasting is **less reliable in the case of millet based on the results of the examined cropyears.**
3. **In practice so far, millet has been regarded as a drought-tolerant plant suitable for late sowing, however, with changes in temperature, the use of an earlier sowing time (late April-May) should be considered.** In our experiments, the postponement of the sowing time resulted in a considerable, significant yield reduction for all varieties.
4. **The different nutrient supply levels** (control, N₄₀P₄₈K₄₈, N₈₀P₇₂K₇₂, N₁₂₀P₉₆K₉₆ kg ha⁻¹) **did not result in a significant effect on the yield in any of the production sites** (sand soil or meadow soil), so millet may be suitable for growing in technologies with low nutrient supply intensity.
5. **The change in the row spacing did not result in a significant effect on the yield of millet,** so the application of sowing at the grain row spacing considered traditional is effective, considering the good weed suppressing effect of millet and its resistance to chemical weed control.
6. There were statistically proven differences between the millet genotypes. **Among the studied varieties, the productivity of the *Maxi* variety significantly exceeded the yield of the other three varieties (*Rumenka*, *Biserka*, *Lovászpatonai*)** in the average of the years and treatments. At the same time, in the case of the latter varieties, the special possibilities of use (different content parameters, different eye color) also justify their cultivation.

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