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Article

Evaluating the Impact of NPK Fertilization Efficiency on Sugar Beet Yield Stability and Agronomic Risk under Increasing Climatic Stress

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Abstract: Optimal and rational mineral nutrition is one of the important factors for stable sugar beet production under climate change conditions. In this study, the effect of five NPK fertilization treatments (0-0-0, 100-0-0, 50-50-50, 100-100-100, and 130-130-130 kg/ha) on root yield, sugar yield, and sucrose content was investigated over a 17-year period (2009–2025). The trial was conducted on an open field in the municipality of Pančevo (Institute Stari Tamiš), on a chernozem soil type. Based on the obtained results, it was established that NPK fertilizers led to a significant increase in yield compared to the control and nitrogen-only fertilization. No statistically significant differences in sugar yield were recorded between the moderate doses (50-50-50 and 100-100-100 kg/ha) and the maximum dose (130-130-130 kg/ha) of applied NPK fertilizer. For root yield, the 100-100-100 and 130-130-130 kg/ha treatments showed a similar effect. Unfavorable environmental conditions (heat stress, drought) during the summer months (July, August) additionally affected the lower efficiency of the maximum NPK fertilizer doses. By analyzing production risks, it was determined that fertilizing sugar beet crops with 100-100-100 kg/ha NPK provides a stable yield with minimal financial risk. It is recommended that under unfavorable environmental conditions, mineral nutrition should be economically more rational and adapted to climate stress conditions.

Keywords: *Beta vulgaris L., climate, Eskridge risk index, NPK fertilization, yield stability*

1. Introduction

Sugar beet (*Beta vulgaris* L., fam. *Amaranthaceae*, 2n = 18) represents an economically significant biennial field crop species and the primary raw material for industrial sucrose production in the temperate climate zone. It is mostly cultivated in the northern part of the hemisphere – in Northern and Eastern Europe, as well as in North America, with the largest world producers being Russia (46.7 Mt, 0.99 Mha), Germany (36.7 Mt, 0.44 Mha), France (32.6 Mt, 0.41 Mha) and the USA (31.0 Mt, 0.44 Mha). According to the latest FAO data, in Serbia sugar beet is cultivated on 46,839 ha, with a total production of 1.92 million tons, which – alongside sunflower and soybean – ranks it among the three leading industrial plant species on domestic agricultural fields [1].

During the technological processing of sugar beet root, in addition to sucrose (the main product), three significant by-products are generated: beet pulp, molasses, and lime cake [2]. Dry pulp is further used in livestock feeding and in livestock production. Molasses serves as a raw material for the production of yeast, acetone, organic acids, enzymes as well as for the

microbiological synthesis of antibiotics and amino acids [2]. In addition, dry pulp and molasses are also used for obtaining bioethanol [3]. Lime cake is used as an effective liming agent for neutralizing acidity and improving the physicochemical properties of soil [4]. Due to the multiple utilization of the raw material, production achieves high economic potential, but its profitability directly depends on the application of adequate agro technical measures, optimization of mineral nutrition and successful control of production risk under conditions of variable climatic and ecological factors [5].

High temperatures, fluctuations in precipitation and increasingly frequent prolonged droughts, which result in a deficit of soil and air moisture, represent some of the most important abiotic stressors that lead to the disruption of stability and affect the level of yield in sugar beet production [6]. The optimal amount of precipitation is important for the uptake of nutrients and redox balance of plants – preventing oxidative stress, cellular dysfunction and biomolecular damage [7]. A crucial role in mitigating the negative effects of abiotic stress and in stabilizing yield is played by the implementation of appropriate agro technical measures such as optimal and timely irrigation, deep tillage for moisture conservation, optimal crop nutrition, timely plant protection based on pest monitoring, as well as the production of genetically more tolerant hybrids [8-10].

The dynamics of macronutrient uptake in sugar beet depends on its developmental stages: at the very beginning of vegetation, plants absorb relatively small amounts of nitrogen (N), phosphorus (P) and potassium (K), when a temporary phosphorus deficiency may occur [11]. During the period of intensive leaf mass growth, plants have extremely high requirements for nitrogen and potassium [12], while in the phase of formation and thickening of the root, the need for nitrogen is moderate and the need for phosphorus and potassium is increased [13-15]. Previous studies have shown that for a root yield of 10 t (with corresponding leaf mass) sugar beet extracts from the soil an average of 60 kg N, 26 kg P, and 120 kg K [16]. Previous scientific findings indicate that the application of high nitrogen doses in years with pronounced moisture deficit and high temperatures often disrupts the balance in nutrient uptake. Under these conditions, elevated nitrogen promotes water loss through leaves and canopy development, negatively affecting root growth, and thereby draining water reserves in the accumulation zone, intensifying oxidative stress and significantly reducing the technological quality of the root [13]. The technological quality of the root is directly related to the sucrose content, while an increase in the proportion of harmful nitrogen compounds represents the main cause of a decrease in sucrose content [17]. On the other hand, optimization of macronutrient ratios, and especially providing adequate amounts of potassium, improves osmotic regulation, protects cell membranes and maintains turgor, which is essential for maintaining photosynthesis during drought periods [18-19].

The application of recommended doses of macronutrients under optimal growing conditions is considered a guarantee of high yield. However, growing crops in years with unfavourable climatic conditions, with the application of fertilization rates that do not follow the actual needs of plants for nutrients, leads to irrational spending of resources and carries high production and economic risk [20]. For that reason, the objective of this paper was to evaluate the effect of different NPK fertilizer doses on the yield and technological quality of sugar beet under conditions of climate extremes, as well as to define through production risk assessment more stable nutrition models and re-evaluate the economic justification of applying maximum doses in stressful years.

2. Materials and Methods

The field experiment was conducted over a 17-year period (2009–2025) at the experimental field of the Research and Development Institute Stari Tamiš in Pančevo, Serbia (44°56’18.83’’N, 20°43’7.19’’E, and elevation 140 m). The soil at the experimental plot is classified as Chernozem, characterized by favorable physicochemical properties and high humus content in the arable layer.

Sowing of sugar beet was carried out during the last decade of March or the first decade of April (between March 22 and April 9). The experiment was arranged in small experimental plots of 100 m^2 (10 x 10 m), and data were not collected from edge-row plants to prevent border effects. Inter-row spacing was 50 cm, with an intra-row plant spacing of 15.9 cm. Predominant commercial

sugar beet hybrids were included in the study, ensuring that the selected hybrids were uniform in yield potential and sucrose content across all seasons.

Five N:P:K fertilization treatments were evaluated (kg/ha): 1) 0-0-0 (control), 2) 10 0-0-0, 3) 50-50-50, 4) 100-100-100, and 5) 130-130-130. Half of the total nutrient requirement was incorporated during autumn deep tillage, while the remaining nitrogen was applied in spring (Table 1).

Table 1. Applied amounts of mineral fertilizers across treatments (kg/ha).

Treatments	Autumn	Spring
0-0-0	-	-
100-0-0	199 KAN	199 KAN + 155 AN
50-50-50	96 KAN + 94 MAP + 100.8 KCl	96 KAN + 76 AN
100-100-100	199 KAN + 188 MAP + 201.6 KCl	199 KAN + 155 AN
130-130-130	244 KAN + 245 MAP + 261.4 KCl	244 KAN + 197 AN

* *Fertilizer composition: KAN (27% N), MAP (12% N, 52% P_2O_5), KCl (60% K_2O), AN (33.5% N).*

During the growing season, standard crop management practices (hoeing, irrigation) and plant protection against weeds, diseases, and pests were applied. Sugar beet root harvesting was carried out, depending on the year, between September 23 and October 30. Following harvest, roots were cleaned of soil and leaves and weighed on a technical scale. After measuring root weight, root yield was calculated and expressed as t/ha. Additionally, sucrose content was determined in sugar beet root samples under laboratory conditions using the polarimetric method [21]. Polarized (pure) sugar yield (t/ha) was calculated using the formula [22]:

$$\text{Polarized sugar yield } (t/ha) = \frac{\text{Root yield } (t/ha) \times \text{Sucrose content } (\%)}{100}$$

All agrometeorological data were retrieved from the European Climate Assessment & Dataset (ECA&D, KNMI, Netherlands; www.ecad.eu) for the geographical coordinates of the experimental site. In addition to primary parameters (temperature and precipitation), tropical days (Tx ≥ 30°C) during the growing season (2009–2025) were also analyzed.

Agrometeorological and collected agronomic data were statistically processed using R software (R Core Team, 2024; packages: ggplot2, corrplot, factoextra, agricolae). Annual and monthly variability of hydrothermal stress during the growing season (April–October) was evaluated using Selyaninov's Hydrothermal Coefficient [23]:

$$HTC = \frac{\sum P}{0.1\ x\ \sum T}$$

where ∑P represents the monthly precipitation sum (mm), and ∑T represents the sum of mean daily air temperatures (°C) for days with temperatures above 10°C. HTC values below 0.5 indicated severe drought, 0.5 to 1.0 moderate drought, 1.0 to 1.5 optimal moisture, and above 1.5 excessive moisture (risk of poor soil aeration and nutrient washing-out).

To evaluate the effect of mineral fertilizer treatments on the examined traits, descriptive parameters were determined: mean, standard deviation (SD), standard error (SE), and coefficient of variation (CV, %). Statistically significant differences between treatments were determined using two-way analysis of variance (ANOVA) and Tukey's HSD post-hoc test at a significance level of α = 0.05.

Pearson's correlation coefficient between agrometeorological and agronomic traits was determined at two significance levels ($p < 0.05$, $p < 0.01$). Additionally, Principal Component Analysis (PCA) was applied, a multivariate statistical method aimed at transforming mutually correlated variables into a smaller number of uncorrelated components while preserving maximum variability [24].

Assessment of yield stability and agronomic risk under adverse agroecological conditions was performed using two stability models: Eskridge's safety-first reliability index [25] and the Finlay–Wilkinson regression model [26].

3. Results and Discussion

3.1. Dynamics of agroclimatic conditions during the experiment

Analysis of Selyaninov's Hydrothermal Coefficient (HTC) and comparative climatic diagrams over the 2009–2025 periods indicates strong variability during the observed period and an increasingly frequent occurrence of extreme agroclimatic conditions during the sugar beet growing season (April–October).

A sugar beet plant requires the largest amounts of water during the stages of intensive leaf canopy development and root enlargement, which occurring in July and August. Analyzing the annual HTC dynamics clearly identifies years with adequate moisture conditions, as well as years in which values during critical phenophases of the crop fall below the severe drought limit (HTC < 0.5, indicated by the red dashed line; Figure 1). The year 2014 was particularly notable for extreme humidity, reaching an absolute HTC maximum in May (exceeding 5.0). In May 2014, long periods of continuous precipitation, elevated river levels, flooding, and consequently high groundwater levels were recorded. Elevated soil moisture and prolonged water retention in the root zone lead to hypoxia [27]. Such conditions cause root hair necrosis, reduced nutrient uptake capacity, and pronounced crop susceptibility to root rot pathogens (such as *Pythium*, *Rhizoctonia*, and *Phytophthora* spp.), which can significantly reduce root yield and quality in later developmental stages [28].

Optimal HTC values in both July and August were not recorded in any of the observed growing seasons; however, optimal conditions were observed in July during 2009 and 2011, and in August during 2020, 2022, and 2023.

In contrast, prolonged water stress occurred during certain growing seasons. In these years, summer months (primarily July and August) were extremely dry, with a complete absence of precipitation that directly threatened crop growth, development, and overall sugar beet yield stability.

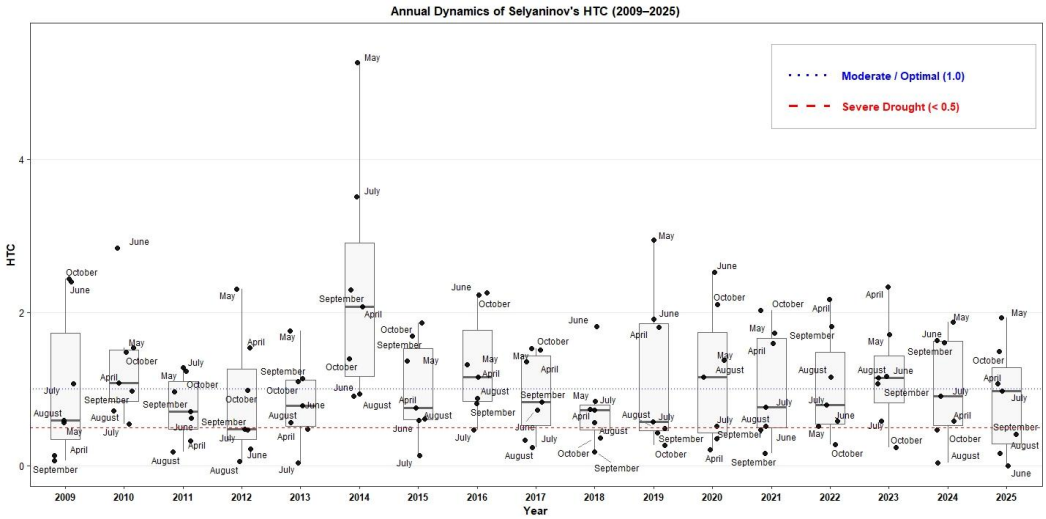

Figure 1. Dynamics of Selyaninov's Hydrothermal Coefficient (HTC) during the sugar beet growing season (2009–2025).

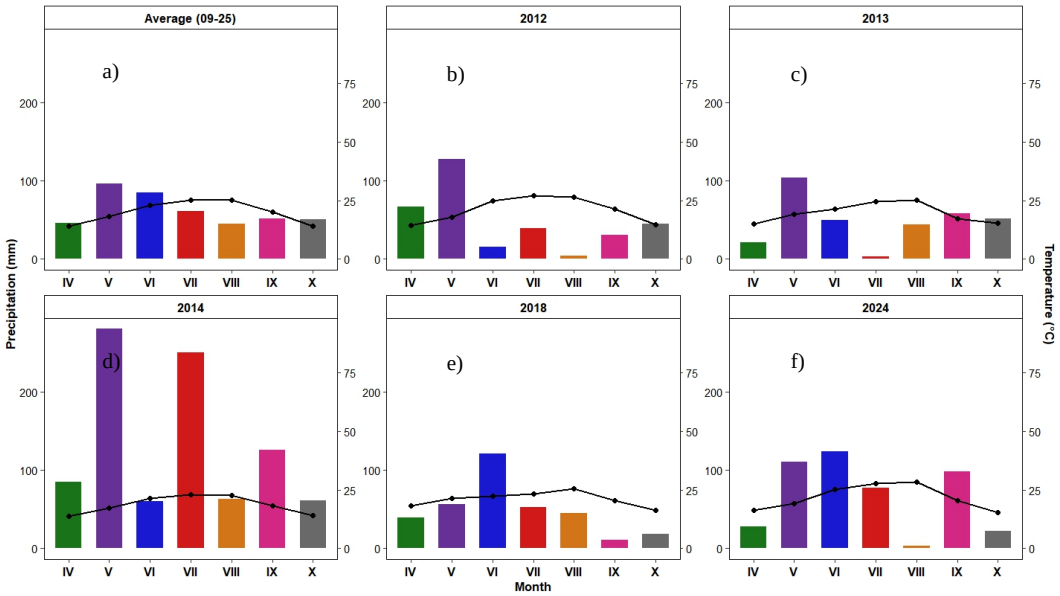

Figure 2. Monthly distribution of total precipitation (bars) and mean air temperature (line) during the sugar beet growing season: (a) 2009–2025 long-term average, (b) 2012, (c) 2013, (d) 2014, (e) 2018, and (f) 2024.

Analysis of mean monthly precipitation and temperature during the sugar beet growing season across the multi-year average (Figure 2a) determined a moderate precipitation distribution with a temperature peak in July and August (around 25°C). Figure 2 (b–f) presents a comparative view of the relationship between precipitation and mean monthly temperatures across five extreme growing seasons. Total water requirements of sugar beet during the growing season in our region are approximately 600 mm [29]; however, precipitation deficits frequently occur in Vojvodina, particularly during summer months during root growth, root enlargement, and sucrose accumulation [30]. In our experiment, 2012 was characterized by severe summer drought conditions (Figure 2b). During emergence and leaf rosette formation (April and May), precipitation amounts were satisfactory, whereas a drastic drop in precipitation occurred during summer months. In August, precipitation was almost entirely absent, which, combined with high mean daily temperatures, and directly threatened the root enlargement phase. In addition to moisture, temperature regimes play a key role in sugar beet physiological processes. Optimal air temperatures for photosynthesis and sugar accumulation in the root range between 20°C and 25°C [9]. At temperatures above 30°C, stomata closure occurs, transpiration increases, and organic matter accumulation and yield are reduced [31].

Similar to 2012, a comparable pattern was observed during 2013 (severe July drought) and 2024 (dry August). The year 2018 was specific due to the occurrence of late autumn drought (August, September, October), which negatively affected final sucrose accumulation and made root harvesting operations considerably more difficult. The year 2014 stood out as extremely humid, characterized by more optimal temperatures, but excessive soil moisture saturation made plants more susceptible to plant diseases.

3.2. Productivity response of sugar beet across fertilization treatments

Analysis of descriptive statistical parameters and Tukey HSD test results following two-way analysis of variance across the 17-year period (2009–2025) confirmed that the applied NPK treatments had a highly significant effect ($p < 0.001$) on root yield, polarized sugar yield (PSY), and sucrose content in the root (Table 2).

The average root yield varied from 40.92 t/ha in the control treatment (0-0-0) to 64.84 t/ha when the highest NPK fertilizer rate (130-130-130) was applied. In comparison, plots receiving only nitrogen fertilization (100-0-0) achieved an average yield of 50.57 t/ha, clearly demonstrating the necessity of balanced macronutrient application. A similar pattern was observed for polarized sugar

yield, which increased with higher nutrient rates—from 6.48 t/ha in the control to 10.46 t/ha in the NPK 130-130-130 treatment. The positive effect of sugar beet fertilization with all three macronutrients can be attributed to their distinct physiological roles in plants. Nitrogen is part of a essential biomolecules, stimulating leaf canopy and photosynthetic system development during early stages; potassium plays a crucial role in osmoregulation, stomata opening, and efficient assimilate transport from leaves to roots during summer months; phosphorus is vital for root growth and development, providing crop stability and more efficient uptake of water and other mineral elements [32].

Table 2. Descriptive statistical parameters, safety-first risk index, stability and agronomic risk parameters of sugar yield, root yield, and sucrose content across fertilization treatments (2009–2025).

Parameter	Unit	Mean	SD	SE	CV (%)	Ymin,90%	Finlay-Wilkinson (b_i)	Coefficient of Determination (R^2)
Sugar yield (SY)								
SY_0-0-0	t/ha	6.48[c]	2.20	0.53	33.98	3.66	0.738	0.81
SY_100-0-0	t/ha	8.04[b]	2.51	0.61	31.25	4.82	0.868	0.86
SY_50-50-50	t/ha	9.37[a]	3.14	0.76	33.48	5.35	1.127	0.93
SY_100-100-100	t/ha	9.75[a]	3.09	0.75	31.70	5.79	1.094	0.90
SY_130-130-130	t/ha	10.46[a]	3.25	0.79	31.10	6.29	1.173	0.93
Root yield (Yield)								
Yield_0-0-0	t/ha	40.92[d]	14.99	3.64	36.63	21.70	0.738	0.84
Yield_100-0-0	t/ha	50.57[c]	17.59	4.27	34.79	28.02	0.899	0.91
Yield_50-50-50	t/ha	57.14[b]	20.84	5.06	36.48	30.42	1.093	0.95
Yield_100-100-100	t/ha	61.64[ab]	21.41	5.19	34.72	34.19	1.114	0.94
Yield_130-130-130	t/ha	64.84[a]	22.13	5.37	34.13	36.47	1.156	0.95
Sucrose Content (%)								
Yield_0-0-0	%	15.99[b]	1.39	0.34	8.71	14.21	0.996	0.93
Yield_100-0-0	%	16.11[b]	1.40	0.34	8.72	14.31	0.968	0.87
Yield_50-50-50	%	16.62[a]	1.70	0.41	10.21	14.44	1.237	0.97
Yield_100-100-100	%	15.96[b]	1.19	0.29	7.43	14.44	0.823	0.88
Yield_130-130-130	%	16.28[b]	1.38	0.33	8.48	14.51	0.975	0.91

Sugar Yield - Polarized sugar yield ($\mathrm{t\ ha^{-1}}$*); Sucrose Content (%); SD - Standard Deviation; SE – Standard error, CV - Coefficient of Variation;* $Y_{\min,90\%}$ *- Eskridge safety-first risk index at 90% probability; Eskridge Index (*$Y_{\min,90\%}$*), minimal expected yield at 90% confidence level under stressful environmental conditions (*$\bar{Y}_i - 1.282 \cdot SD_i$*);* b_i*, regression slope indicating environmental sensitivity (*$b_i > 1.0$ *high responsiveness to favorable environments,* $b_i < 1.0$ *high tolerance to stressful environments);* R^2*, coefficient of determination for linear stability model*

However, although the highest yields were recorded under the highest fertilizer rates, no statistically significant differences in sugar yield were observed among fertilizer treatments 130-130-130, 100-100-100, and 50-50-50. Similarly, for root yield, no statistically significant difference was found between crops fertilized with 130-130-130 and 100-100-100. The absence of statistically significant differences in root and sugar yields between moderate and maximum fertilizer doses serves as an important argument for rationalizing mineral nutrition and reducing input costs under changing climatic conditions. High nitrogen level in later developmental stages can have a harmful effect. Nitrogen promotes vegetative canopy growth, and during autumn, high nitrogen level can leach into deeper soil layers. Furthermore, high variability was determined (CV = 31.10% to 36.63%) for both yield parameters, clearly indicating pronounced yield instability under variable

agroclimatic conditions across the multi-year study period, which aligns with findings of other authors [33].

Sucrose content varied within a narrow range from 15.96% (100-100-100) to 16.62% (50-50-50), with a relatively low coefficient of variation (CV = 7.43%–10.21%). These results indicate that total sugar yield variations per hectare primary depend on root yield biomass rather than fluctuations in sucrose content percentage. Root sucrose percentage in sugar beet is a highly heritable trait, unlike root weight, which is under stronger environmental influence [34].

Agronomic risk assessment, based on the minimum guaranteed yield under unfavorable years at a 90% confidence level (Eskridge safety-first reliability index Ymin,90%), revealed that NPK fertilization at 130-130-130 provided the highest absolute safety under stressful conditions (guaranteed minimum of 36.47 t/ha root yield vs. 21.70 t/ha in control; 6.29 t/ha sugar yield vs. 3.66 t/ha in control; 14.51% sucrose content vs. 14.21% in control). However, the moderate rate (100-100-100) provided as much as 34.19 t/ha root yield and 5.79 t/ha sugar yield, achieving a high yield safety level with lower fertilizer input and reduced economic risk. Eskridge index evaluation can be of key importance for producers of sugar beet, as multi-year mean yields often cannot serve as a reliable basis for decision-making due to high interannual climate variability [35]. When planning crop production, it is essential to ensure stable profit while minimizing financial burden on producers, particularly under extreme agroclimatic conditions.

Using the Finlay–Wilkinson stability model (bi), fertilization treatments were differentiated based on regression coefficients. For all three evaluated traits in control plots and single-nitrogen application treatments, regression values were below 1.0, indicating lower sensitivity to poor environmental conditions, but also limited potential for yield response in agroecologically favorable years. Except for sucrose content, complete NPK treatments (50-50-50, 100-100-100, and 130-130-130) achieved regression coefficients above 1.0 for root and sugar yields along with high model linearity ($R^2 > 0.90$). These results demonstrate that more intensive mineral nutrition in sugar beet delivers higher yields in favorable environments while mitigating yield losses during adverse climatic periods. For sucrose content, only the NPK 50-50-50 treatment recorded a regression coefficient greater than 1.0.

3.3. Pearson correlation analysis between climatic stress and yield performance

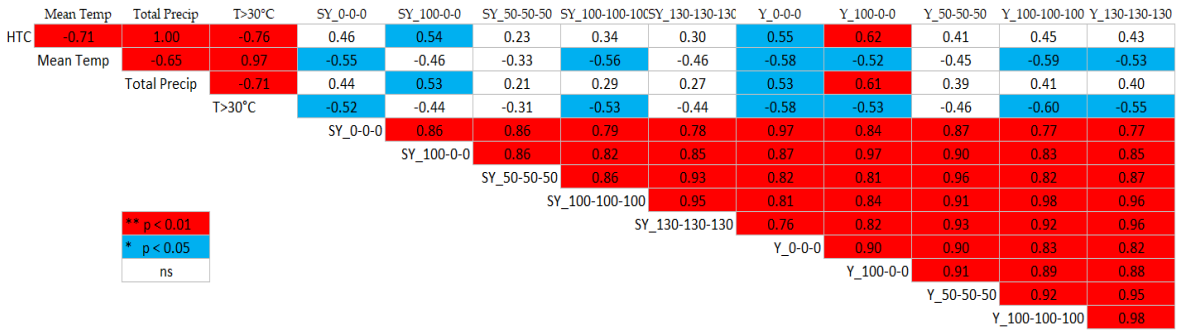

Figure 3. Pearson correlation matrix between microclimate stress indices and sugar beet productivity parameters (*p < 0.05, p < 0.01). *HTC – hydrothermal coefficient; Mean Temp – mean monthly temperature; Total Precip – total precipitation; T > 30°C – number of days with temperatures above 30°C. Treatments: SY1–SY5 (Sugar yield) and Y1–Y5 (Root yield) represent NPK fertilization rates: 1 (0-0-0 kg/ha); 2 (100-0-0 kg/ha); 3 (50-50-50 kg/ha); 4 (100-100-100 kg/ha); 5 (130-130-130 kg/ha). ns– non significant.*

Correlation analysis between agrometeorological parameters (HTC, mean temperature, total precipitation, number of days with T > 30°C) and the two productivity traits (root yield and sugar yield) revealed statistically highly significant relationships among these parameters (Figure 3). A highly significant negative correlation was found between HTC and mean temperature, as well as the number of days with temperatures above 30°C. This relationship confirms the compound impact

of drought and heat stress, where soil and atmospheric moisture deficits were directly accompanied by extreme temperatures and intense solar radiation [36].

The significant negative correlation of total precipitation with mean temperature and tropical days further supports this conclusion. These results align with multi-year agroclimatic analyses for Vojvodina, where authors established that extreme summer droughts are regularly accompanied by heat waves that further deplete soil water reserves [30].

Sugar yield showed positive correlations with HTC and total precipitation, whereas negative correlations were recorded with mean temperature and tropical days. Statistically significant positive correlations were determined between sugar yield and HTC, as well as total precipitation, under single-nitrogen fertilization. Statistically significant negative correlations were found between sugar yield and mean temperature, as well as tropical days, in the control treatment and under NPK 100-100-100 kg/ha.

For root yield, statistically significant positive correlations were determined with HTC and total precipitation in single-nitrogen and control treatments, whereas statistically significant negative correlations were found with mean temperature and tropical days across all treatments, except under NPK 50-50-50.

All yield parameters (root and sugar) showed statistically highly significant positive inter-correlations, with r values ranging from 0.77 to over 0.98. This proves that applied management practices and fertilization treatments respond in a similar manner to variable climate conditions despite annual fluctuations, although absolute yield levels remain directly dependent on abiotic stress intensity during specific growing seasons. As highlighted by [31], in years with prolonged drought and elevated temperatures, climatic conditions act as the dominant factor over applied agronomic practices.

3.4. PCA analysis

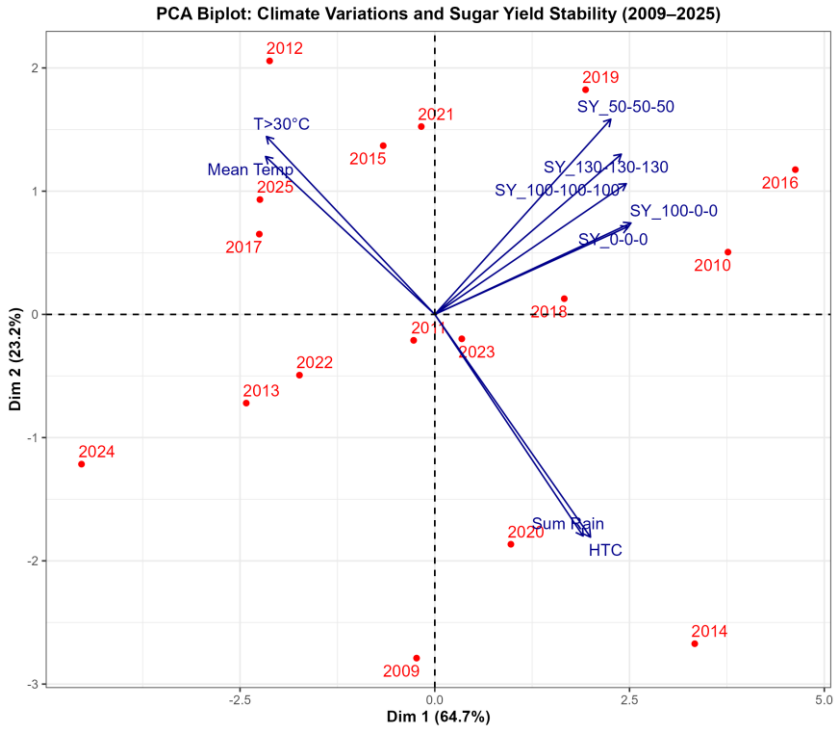

Figure 4. Principal Component Analysis (PCA) biplot illustrating climate variations and sugar yield stability across experimental years (2009–2025).

The results of the principal component analysis (PCA) show that the first two principal components cover a total of 87.9% (Figure 4) of the total variability of the analyzed data (PC1 = 64.7%, PC2 = 23.2%). This high cumulative percentage indicates that the obtained results of the

analysis are extremely reliable. The high proportion of variance explained by the first principal component (64.7%) indicates that the primary axis of variation in this experiment is defined by the contrast between thermal stress and moisture availability.

On the biplot, the first principal component separated the vectors of the observed characteristics so that the vectors representing thermal parameters (mean temperature (Mean Temp) and the frequency of tropical days (T > 30°C)) grouped on the left (negative) side of the axis, while the fertilization treatments (Sugar Yield variants) and the vectors of precipitation (Sum Rain) and hydrothermal coefficient (HTC) separated on the right side of the PC1 axis. The vectors of thermal parameters are located in the left quadrant and form an acute angle with each other, which confirms their high positive correlation. On the other hand, the vectors of precipitation (Sum Rain) and hydrothermal coefficient (HTC) are located in the fourth quadrant, positioned orthogonally with the thermal factors, thereby confirming the contrast between arid/warm and humid conditions during vegetation [37].

The yield vectors depending on fertilizer rates are all concentrated in the first quadrant and show pronounced collinearity. Small angles between these vectors indicate that total sugar yields on average move in a similar direction, but the position of their tips reveals subtle differences in the efficiency of individual doses depending on the year. An angle close to 90° or an obtuse angle between the thermal stress vector (T > 30°C) and the yield vectors illustrates the negative impact of extreme temperatures on sugar accumulation, while the proximity of the precipitation/HTC vectors to the horizontal axis indicates a more favorable impact of humid years on productivity.

Vegetation seasons are clearly separated on the plot in relation to environmental conditions. Extremely dry and warm years (2012, 2015, 2017, 2021, 2023, 2024 and 2025) are positioned on the negative side of the PC1 axis and are in negative correlation with the yield vectors and positive with the thermal indices. Year 2012 stands out in particular, located far on the left side and at the top, which indicates the unfavorable effects of heat waves and precipitation deficits on crop stability. In these years, the application of high fertilizer doses did not yield the expected effect due to pronounced abiotic stress.

The PC2 axis separates vegetation seasons into years with a higher sum of precipitation and HTC and those with a greater number of tropical days and mean temperatures. Years with a sufficient amount of precipitation and a more favorable HTC index, such as 2014, 2020 and 2009, are placed in the lower part of the graph, following the direction of the Sum Rain and HTC vectors.

Vegetation seasons with more stable yields are distributed on the positive side of the PC1 axis (2010, 2016, 2019). The year 2019 stands out in the upper right quadrant, near the vector of the moderate fertilizer dose (SY_50-50-50), which suggests that in the climatic conditions that were during the vegetation season in the course of this year, lower fertilizer doses achieved high agronomic efficiency without the risk of excessive plant load [38].

4. Conclusions

The application of NPK fertilizers containing all three macroelements (50-50-50, 100-100-100, and 130-130-130) significantly increased root and sugar yields compared to the control and the application of nitrogen fertilizer alone, but no statistically significant differences in sugar yield were found between the moderate doses (50-50-50 and 100-100-100 kg/ha) and the maximum dose (130-130-130 kg/ha), while for root yield there was no significant difference between the 100-100-100 and 130-130-130 kg/ha treatments. Environmental conditions had a major impact on all observed traits. Heat stress (high mean temperatures and tropical days) in combination with a deficit of precipitation had a negative effect on root and sugar yields in sugar beet crops. This was particularly intensified during the summer months (July and August). During several growing seasons (2012, 2015, 2017, 2024), summers were extremely dry and warm, and the application of maximum fertilizer doses did not produce the expected agronomic effect. By comparing stability models and agronomic risk assessment (Eskridge and Finlay-Wilkinson), it is concluded that under stressful conditions, the application of NPK fertilizer at 100-100-100 kg/ha can provide optimal and stable

root and sugar yields in sugar beet crops compared to the maximum dose of 130-130-130 kg/ha, with a significantly lower economic and production risk. The obtained results indicate the necessity for more optimal and rational mineral nutrition of sugar beet under increasingly frequent extreme agroclimatic conditions.

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Declaration of Generative AI Use: The author(s) declare that no generative artificial intelligence (GenAI) tools were used in the preparation of this manuscript.

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