https://doi.org/10.61308/JYPI2067

Influence of long-term mineral fertilization on the content of main macronutrients in the aboveground biomass of maize hybrid Kneja-435

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Citation: Nankova, M., Sartmachev, T., Slavov, M., & Tsenov. N. (2025). Influence of long-term mineral fertilization on the content of main macronutrients in the aboveground biomass of maize hybrid Kneja-435. *Bulgarian Journal of Crop Science*, *62*(3) 11-29

Abstract: The research was conducted in a long-term fertilizer experiment, initiated in 1967 on Haplic Chernozems in the Experimental Field of DAI General Toshevo. It covers 49 fertilizer combinations with different norms and ratios between NPK. The changes in the concentration of the main macroelements in the vegetative biomass (VBM), the corn cob and the grain of hybrid Kneja-435 for the period 2020-2023 were investigated. The tested fertilizer norms of nitrogen and phosphorus are 0, 60, 120 and 180 kg/ha, and 0, 60 and 120 K_2O kg/ha for potassium. It was established that the nitrogen content in the corn grain increases with the growing norm of nitrogen fertilization in all PK combinations (from 1.26% to 1.77%). A similar trend was also found for the concentration of nitrogen in VBM (leaves + stems) - from 0.65% to 1.07%. The concentration of phosphorus in the grain also grows with increasing nitrogen fertilization norm, but the trend is less pronounced. The highest concentration of potassium was founded in VB, followed by that of the corn cob and the grain. Compared to the dynamics in the concentration of nitrogen and phosphorus depending on the increasing nitrogen fertilizer and its combinations with PK, that of potassium is the weakest. In the chemical composition of the corn cob, the influence of the nitrogen norms and its combination with PK is the least pronounced. Results show that the content of macronutrients in the grain were distinguished by lower values of the coefficient of variation at all levels of nutritional regime compared to those of the non-economic part of the production. Nitrogen in the grain with increasing nitrogen fertilization has a strong correlative relationship with its concentration in the VB.

Key words: maize; long-term mineral fertilization; NPK concentration by organs

INTRODUCTION

The high productivity potential of maize, as well as its adaptability to be cultivated over a wide geographical range, makes it a strategic crop globally. According to FAO data (2010), maize ranks third after wheat and rice in global cereal production. However, over the last decade, its position has fluctuated frequently. In recent years, it has often occupied the top position in the production of field crops worldwide. According to USDA data (2023-2024), maize production is expected to exceed 1.22 billion metric tons.

The productivity and quality of maize are directly related to the cultivation technology and the timely execution of various agronomic practices. Mineral fertilization, as a key component of conventional farming technology, is fundamental to increasing maize productivity. Intensive farming involves using high-yielding varieties and intensive mineral fertilization. However, this approach does not always lead directly to higher productivity. On the contrary, excessive fertilization can result in significant financial losses and various environmental issues (Karasu 2012). According to Fageria et al. (2008), part of the nitrogen application norm can be compensated for by the additional use of biologically active foliar products. This practice is particularly useful under unfavorable soil and climatic conditions that hinder nutrient uptake from the soil (Hirschi 2009). Maize is sensitive to deficiencies in micronutrients, particularly manganese and zinc. When combined with high nitrogen norms, its sensitivity to pests and diseases increases (Reuveni & Reuveni 1998).

Numerous studies have evaluated the effects of fertilization on maize yield (Muchow 1988; Wolfe et al., 1988; Uhart & Andrade 1995; Pandey et al., 2000; Zand-Parsa & Sepaskhah 2001; Benjamin et al., 2003; Cai & Qin 2006; Stoyanov 2007; Vulchinkov et al., 2013; Mikova et al., 2013), with varying conclusions. These studies are often based on short-term research, while sustainable farming practices require long-term field and laboratory experiments to better understand the complex interactions between soil, plants, climate, and management (Army & Kemper 1991).

The concentration and uptake of nutrients, especially essential macronutrients like nitrogen, phosphorus, and potassium, determine the biological value of the produced biomass (Hussain et al., 2007; Wylupek et al., 2014). Nutrients never act independently; they exhibit synergistic and antagonistic interactions (Bak et al., 2016). Nenova et al. (2019) observed significant dynamics in the concentrations of major macronutrients in maize plant organs depending on the fertilization norms and stages of crop development. This suggests the need for research on the effects of macronutrient fertilization on the formation of key maize plant organs that contribute to its productivity and quality.

The purpose of the present study is to evaluate the effects of long-term mineral fertilization with different norms and ratios of nitrogen, phosphorus, and potassium on the concentration of major macronutrients in the aboveground biomass of maize hybrid Kneja-435.

MATERIALS AND METHODS

Dobrudzha Agricultural Institute is located in the eastern flat part of Dobrudzha. The soil cover is predominantly represented by slightly leached chernozem soils formed on loess (Haplic Chernozems). These soils are characterized by a relatively thick humus horizon (60-80 cm), heavy sandy-clay texture, and undifferentiated profile. The physical clay content is between 45-60%, and the humus content reaches 3.0-3.5% (Nankova, 2012).

The study was conducted on a stationary field trial initiated in the autumn of 1966 with a two-field crop rotation of wheat and maize in non irrigated conditions. The effect of systematic mineral fertilization on crop productivity includes testing 4 nitrogen and phosphorus fertilization norms (0, 60, 120, and 180 kg/ha) and 3 potassium fertilization norms (0, 60, and 120 kg/ha). The trial was designed using the "Latin square" method, with experimental plots of 63 m², totaling 48 variations (4 x 4 x 3) and replicated five times. The experimental scheme also includes a 49th variant ($N_{180}P_{180}K_{180}$) in order to monitor the influence of the highest fertilizer rates of macro elements in the ratio N:P:K=1:1:1, also present in the other tested rates. The fertilizers used were ammonium nitrate, triple superphosphate, and potassium chloride. Phosphorus and potassium fertilizers were applied by hand before soil tillage, and nitrogen fertilizers were also applied by hand before maize sowing. The study covers the period from 2020 to 2023, using the Bulgarian hybrid Kneja-435.

Agrochemical plant analyses were performed after sampling the vegetative biomass (leaves + stems), cobs, and grains to determine biological yield at technical maturity. After drying, the samples were prepared for analysis in the Agrochemical Laboratory of the Dobrudzha Agricultural Institute, General Toshevo. Nitrogen, phosphorus, and potassium concentrations in the vegetative biomass (VBM), cob, and grain were determined by classical methods: the Kjeldahl method (for nitrogen), colorimetrically for phosphorus (using the yellow molybdate-vanadate method), and by flame photometry for potassium (Stanchev et al., 1968; Stanchev & Boboshevska, 1974).

The resulted data were statistically processed using variance analysis, F test and LSD (Least Significant Difference) test, which are commonly utilized in the multi-criterial statistical analysis. We used the SPSS version 13.0 statistical package. Significance of the treatments' effect was considered at 0.05 probability level. After performing the analysis of variance, we compared the means for each treatmens using the Waller-Duncan's Multiple Range Test. Finally, Pearson correlation coefficients ("R coefficients") were computed and tested for significance.

RESULTS AND DISCUSSION

The variance analysis of the concentration of major macronutrients shows significant dynamics depending on the experimental factors dur-

Table 1. Analysis of Variance of NPK concentration in maize organs according to the main NPK soil fertilization by years of investigation

Dependent Variable (df=11)	df	2020		2021		2022		2023	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.
N_0									
N %-VBM	11	23,521	,000	179,212	,000	113,207	,000	300,224	,000
P_2O_5 %-VBM	11	372,831	,000	1175,496	,000	727,158	,000	153,710	,000
K_2O %-VBM	11	565,182	,000	885,035	,000	454,818	,000	671,748	,000
N%-Cob	11	15,174	,000	91,690	,000	110,701	,000	228,079	,000
P_2O_5%-Cob	11	104,834	,000	2,530	,063^{NS}	230,279	,000	,989	,504^{NS}
K_2O%-Cob	11	376,932	,000	72,354	,000	331,745	,000	139,194	,000
N%-Grain	11	12,975	,000	45,178	,000	13,263	,000	36,444	,000
P_2O_5%-Grain	11	10,320	,000	46,934	,000	149,502	,000	17,215	,000
K_2O%-Grain	11	15,835	,000	13,124	,000	7,329	,001	10,116	,000
N_{60}									
N %-VBM	11	86,209	,000	418,018	,000	199,030	,000	733,225	,000
P_2O_5 %-VBM	11	1165,455	,000	3512,727	,000	708,856	,000	114,000	,000
K_2O %-VBM	11	587,330	,000	918,818	,000	303,753	,000	577,083	,000
N %-VBM	11	50,104	,000	26,338	,000	2,493	,066^{NS}	174,332	,000
P_2O_5%-Cob	11	186,778	,000	2,843	,043^{NS}	95,101	,000	71,650	,000
K_2O%-Cob	11	153,622	,000	284,332	,000	541,535	,000	148,918	,000
N%-Grain	11	90,100	,000	67,045	,000	41,308	,000	121,517	,000
P_2O_5%-Grain	11	33,487	,000	164,522	,000	70,358	,000	16,436	,000
K_2O%-Grain	11	19,791	,000	12,573	,000	5,365	,004	11,200	,000
N_{120}									
N %-VBM	11	315,879	,000	273,710	,000	575,400	,000	66,235	,000
P_2O_5 %-VBM	11	1695,424	,000	8906,073	,000	2238,286	,000	290,375	,000
K_2O %-VBM	11	1059,048	,000	608,010	,000	750,905	,000	1,309	,325^{NS}
N%-Cob	11	20,566	,000	21,584	,000	83,418	,000	114,667	,000
P_2O_5%-Cob	11	196,204	,000	4,815	,006	216,027	,000	187,069	,000
K_2O%-Cob	11	338,843	,000	155,802	,000	165,115	,000	110,980	,000
N%-Grain	11	64,065	,000	30,009	,000	25,818	,000	65,749	,000
P_2O_5%-Grain	11	66,420	,000	36,401	,000	141,065	,000	19,593	,000
K_2O%-Grain	11	129,523	,000	38,162	,000	7,745	,001	28,743	,000
N_{180}									
N %-VBM	11	380,369	,000	291,364	,000	433,941	,000	483,659	,000
P_2O_5 %-VBM	11	2611,140	,000	1109,761	,000	1752,515	,000	176,818	,000
K_2O %-VBM	11	1229,223	,000	654,429	,000	493,727	,000	413,400	,000
N%-Cob	11	33,810	,000	41,338	,000	49,309	,000	521,790	,000
P_2O_5%-Cob	11	79,653	,000	1,324	,318^{NS}	38,140	,000	998,424	,000
K_2O%-Cob	11	189,818	,000	127,017	,000	740,294	,000	397,897	,000
N%-Grain	11	81,664	,000	104,790	,000	25,659	,000	43,752	,000
P_2O_5%-Grain	11	196,320	,000	23,080	,000	40,889	,000	32,993	,000
K_2O%-Grain	11	36,266	,000	16,036	,000	4,880	,005	59,159	,000

ing the years of the study (Table 1). In 2020, all established differences in NPK concentrations in the maize organs were statistically significant, especially concerning nitrogen fertilization levels.

In 2021, except for changes in phosphorus content in the cob for the N_{120} treatment, all other changes in macronutrient concentrations in the studied organs were significant. In 2022, only non-significant changes in nitrogen concentration in the cob for the N_{60} variant were observed. In 2023, non-significant differences were related to phosphorus concentration in the cob (N_0) and potassium in vegetative biomass (N_{120}).

The results clearly indicate that macronutrient content in maize grain is significantly influenced by fertilization norms and NPK combinations, regardless of the year's conditions.

For the entire study period, statistically non-significant dynamics in macronutrient concentrations were observed in the control variant for phosphorus concentration in the cob, based on the independent effect of "*PK fertilization*" fac-

Table 2. Analysis of Variance of NPK concentration in maize organs according to the main NPK soil fertilization and percent of the total variability explained by factors averaged for 2020-2023

Dependent Variable	Source (Factor)	df	N_0		N_{60}		N_{120}		N_{180}	
			p-value	SS, %	*p-value*	SS, %	p-value	SS, %	p-value	SS, %
N%-V.mass	Years (1)	3	*0.000*	93.0	*0.000*	78.4	*0.000*	68.2	*0.000*	66.1
	PK var. (2)	11	*0.000*	2.2	*0.000*	6.8	*0.000*	11.1	*0.000*	10.6
	1 x 2	33	*0.000*	4.8	*0.000*	14.8	*0.000*	20.7	*0.000*	23.3
P_2O_5%-V.mass	Years (1)	3	*0.000*	7.5	*0.000*	7.3	*0.000*	92.6	*0.000*	80.0
	PK var. (2)	11	*0.000*	74.4	*0.000*	73.1	*0.000*	2.5	*0.000*	6.3
	1 x 2	33	*0.000*	18.1	*0.000*	19.6	*0.000*	4.9	*0.000*	13.6
K_2O%-V.mass	Years (1)	3	*0.000*	77.2	*0.000*	74.3	*0.000*	71.6	*0.000*	78.0
	PK var. (2)	11	*0.000*	15.8	*0.000*	17.1	*0.000*	9.7	*0.000*	7.2
	1 x 2	33	*0.000*	7.0	*0.000*	8.6	*0.001*	18.7	*0.000*	14.3
N%-Cob	Years (1)	3	*0.000*	83.3	*0.000*	80.6	*0.000*	10	*0.000*	20.8
	PK var. (2)	11	*0.000*	4.4	*0.000*	5.1	*0.000*	57.1	*0.000*	51.9
	1 x 2	33	*0.000*	12.3	*0.000*	14.3	*0.000*	32.9	*0.000*	27.3
P_2O_5%-Cob	Years (1)	3	*0.000*	30.0	*0.000*	22.8	*0.000*	59.5	*0.000*	53.9
	PK var. (2)	11	*0.182^{NS}*	21.5	*0.000*	24.3	*0.000*	17.0	*0.000*	9.3
	1 x 2	33	*0.380^{NS}*	48.5	*0.000*	52.9	*0.000*	23.5	*0.000*	36.8
K_2O%-Cob	Years (1)	3	*0.000*	16.1	*0.000*	9.2	*0.000*	48.7	*0.000*	66.4
	PK var. (2)	11	*0.000*	18.6	*0.000*	19.5	*0.000*	27.0	*0.000*	20.0
	1 x 2	33	*0.000*	65.3	*0.000*	71.3	*0.000*	24.3	*0.000*	13.6
N%-Grain	Years (1)	3	*0.000*	82.3	*0.000*	57.3	*0.000*	71.4	*0.000*	68.8
	PK var. (2)	11	*0.000*	6.6	*0.000*	14.2	*0.000*	16.7	*0.000*	22.1
	1 x 2	33	*0.000*	11.1	*0.000*	28.5	*0.000*	11.9	*0.000*	9.1
P_2O_5%-Grain	Years (1)	3	*0.000*	46.0	*0.000*	53.1	*0.000*	23.5	*0.000*	27.4
	PK var. (2)	11	*0.000*	28.9	*0.000*	26.2	*0.000*	34.1	*0.000*	29.3
	1 x 2	33	*0.000*	25.1	*0.000*	20.7	*0.000*	42.4	*0.000*	43.4
K_2O%-Grain	Years (1)	3	*0.000*	45.8	*0.000*	65.8	*0.000*	43.9	*0.000*	63.2
	PK var. (2)	11	*0.000*	17.6	*0.000*	11.9	*0.000*	23.7	*0.000*	15.2
	1 x 2	33	*0.000*	36.6	*0.000*	22.3	*0.000*	32.4	*0.000*	21.6

tor, as well as its interaction with the "*year*" factor (Table 2).

In all other nitrogen fertilization norms, changes in macronutrient concentrations in maize organs were maximally reliable. The nitrogen and potassium content in vegetative biomass (VBM) was most strongly influenced by annual weather conditions. The influence of meteorological components on nitrogen concentration in VBM decreased with increasing nitrogen fertilization norms. This increased the impact of PK fertilization and its interaction with nitrogen norms. Potassium concentration in VBM was less affected by nitrogen fertilization, with significant changes in PK fertilization's influence under low nitrogen (N_0, N_{60}) and higher nitrogen norms (N_{120}, N_{180}).

The concentration of nitrogen in the cob was greatly affected by annual weather conditions, especially in the low nitrogen (N_0) treatments. High norms of nitrogen fertilization lead to an increase in the strength of the independent influence of PK fertilization. Under such conditions, the interaction between nitrogen and PK fertilization had the most significant impact on potassium concentration in the cob.

Nitrogen concentration in maize grain was primarily influenced by annual weather conditions. Similar to VBM, with increasing nitrogen norms, the influence of weather conditions decreased, while the impact of PK fertilization increased. A similar trend was observed for potassium concentration, which varied depending on nitrogen fertilization norms.

A significant differentiation was also observed in the influence of experimental factors on phosphorus concentration in maize grain. Weather conditions had a greater impact under nitrogen deficiency. Under optimal and high nitrogen fertilization norms, the impact of PK fertilization on phosphorus concentration increased, but the combined effect of both factors remained dominant.

The results this far, indicate that meteorological conditions during the growing season significantly influenced macronutrient concentrations in VBM and grain. The combination of two primary meteorological components - rainfall and temperature - during the study period created unique and distinct growing conditions for maize (Fig. 1). Favorable moisture conditions during the growing season were observed in 2021 (304.10 mm) and 2020 (286.30 mm), exceeding the climatic norm by 11.05% and 4.45%, respectively.

In 2022 and 2023, the total growing season rainfall was 91.13% and 58.66% of the climatic norm, respectively. Rainfall was distributed extremely unevenly during all four years. August recorded virtually no rainfall, with totals ranging from 7.4 mm (2022) to 0.2 mm (2023). A similar trend was observed in July.

In terms of temperature, April temperatures were significantly below the climatic norm, par-

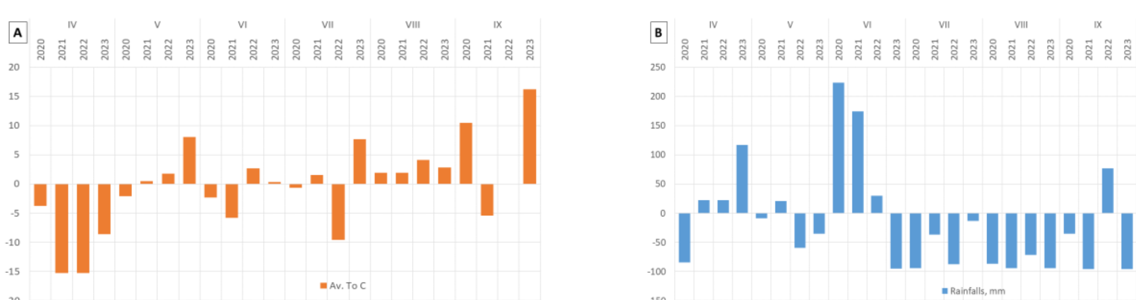

Figure 1. Dynamics of the main meteorological components: A – monthly average air temperatures, and B – total precipitation during the corn growing season as a percentage of their respective climatic norm values for the period 1999-2019

ticularly in 2021 and 2022. In subsequent months, temperatures exceeded the norm, especially in August. This trend continued, to a lesser extent, in September. The year 2023 was notably different from the other years, with higher average temperatures during the growing season and the lowest amount of rainfall, particularly during the tasseling and grain-filling periods.

The nitrogen concentration in VBM during the first three years of the study under natural fertility conditions (N_0) of slightly leached chernozem, showed less differentiation depending on the phosphorus and potassium combinations (Fig. 2). The average values for the 12 PK combinations ranged between 0.40% and 0.49% N, and in 2023, this value was 1.32% N, varying from 1.07% to 1.61% N depending on the PK combinations. Under conditions of severe water stress combined with high temperatures, serious disturbances in nutrient transport occurred. In this case, the VBM in the final stage (BBCH 90-99) retained high nitrogen concentrations. Nitrogen fertilizer norms of N_{120} and N_{180} deepened the differences in nitrogen concentration in vegetative biomass depending on PK fertilization, compared to nitrogen fertilization at 0 and 60 kg N/ha. The maximum nitrogen concentration for each year was reached with the N_{180} + PK combinations.

Similar trends were observed for nitrogen concentration in the cob. The average nitrogen content in the cob during favorable years for maize development was around 0.30% N. Under stress conditions, nitrogen concentration in the cob was nearly twice as high, indicating difficulty in transferring nitrogen from the cob to the grain. Under such conditions during the growing season, the differentiation between the PK combinations was highly pronounced—from 0.56% N ($P_{120}K_{120}$) to 1.42% N ($P_{60}K_0$). The combination of nitrogen with $P_{120}K_{120}$ resulted in the lowest nitrogen content in the cob, on average.

With all nitrogen fertilizer norms, the study years had a significant impact on nitrogen concentration in the grain. A clear trend was observed for higher nitrogen concentrations under stress conditions during critical growth phases. For exam-

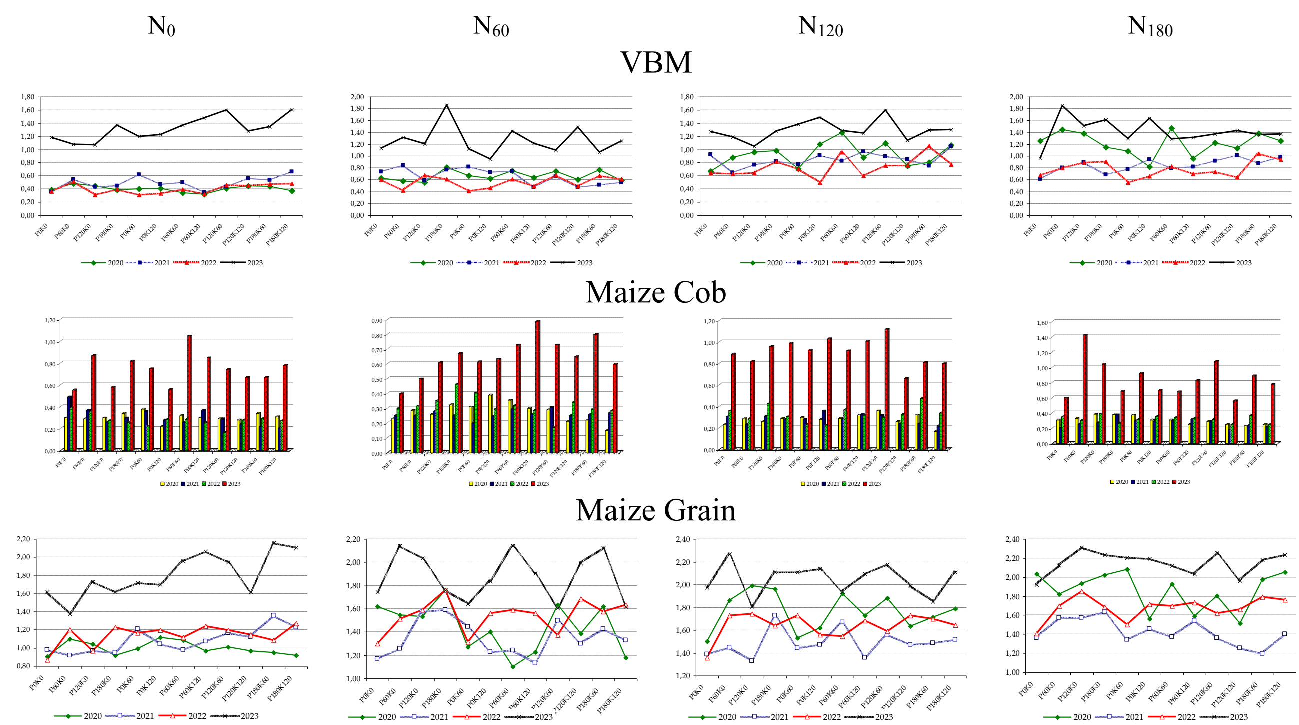

Figure 2. Nitrogen content in the organs of the aboveground biomass of maize, depending on NPK norms and ratios by year of study (N%)

ple, the increase in nitrogen concentration for PK combinations without nitrogen in 2023 compared to 2020 was 80.46%. For N_{60}, it was 30.58%; for N_{120}, 16.24%; and for N_{180}, 15.49%. There was a strong positive influence of all N_0 + PK combinations compared to the application of phosphorus or potassium fertilizers alone. The highest nitrogen concentrations in maize grain were observed with increasing nitrogen norms when combined with phosphorus norms of P_{120} and P_{180}.

On average, over the study period, there was clear differentiation in nitrogen concentrations in maize organs, depending on the combinations of nitrogen, phosphorus, and potassium applied to the soil (Table 3). In the control variants (without nitrogen fertilization), the studied maize organs in the aboveground biomass had higher nitrogen content with combinations including high phosphorus and potassium fertilizer norms ($P_{180}K_{120}$).

Testing the 12 PK fertilizer combinations in combination with increasing nitrogen norms formed the basis for increasing nitrogen concentration in maize organs when lower phosphorus and potassium norms were applied. At extremely high nitrogen fertilizer norms (N_{180}), the grain had the highest nitrogen concentration when combined with phosphorus norms of P_{120} or P_{180}. Generally, nitrogen, rather than phosphorus and potassium, is the main focus in maize cultivation practices. In their detailed study on maize response to different nutrient sources and application methods, Katoch et al. (2024) found significant changes in the concentrations of several macro- and micronutrients and their impact on yield structure and physical characteristics.

According to Chien et al. (2011), phosphorus application results may vary significantly depending not only on the norm but also on the fertilizer source. The natural phosphorus status of the soil, combined with excessively high phosphorus application norms, poses a risk of excessively high P concentrations, resulting in increased uptake in non-economic parts of the crop and yield harm. This underscores the need for further studies on nutrient uptake under different nutrient regimes for specific soil types and crops. Interest in phosphorus concentration in maize organs is substantial. The results obtained show high sensitivity and clearly expressed dynamics in phosphorus concentration values, both by year and nitrogen norms combined with PK fertilization (Fig. 3). This differentiation was well expressed in all studied organs, particularly in grain.

Table 3. Nitrogen content in maize organs depending on nitrogen norm and its combination with PK, averaged for 2020-2023 (N%)

PK variants	VBM				Maize cob				Maize grain			
	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}
P_0K_0	0.57 a	0.78 e	0.88 c	0.88 a	1.09 a	0.30 a	0.45 d	0.37 b	1.52 a	1.46 b	1.56 a	1.68 b
$P_{60}K_0$	0.65 d	0.79 f	0.84 a	1.22 j	1.15 b	0.34 bc	0.41 b	0.58 i	1.60 d	1.61d	1.83 e	1.81 f
$P_{120}K_0$	0.57 a	0.76 cd	0.86 b	1.17 i	1.18 b	0.38 d	0.49 f	0.52 h	1.53 b	1.68 e	1.72 c	1.92 h
$P_{180}K_0$	0.65 d	1.00 h	0.97 f	1.09 f	1.18 bc	0.43 f	0.47 e	0.43 e	1.59 c	1.72 f	1.86 f	1.89 h
P_0K_{60}	0.63 c	0.75 c	0.89 d	0.93 b	1.27 d	0.38 d	0.43 c	0.48 f	1.72 e	1.42 a	1.70 bc	1.78ef
P_0K_{120}	0.61 b	0.69 a	0.99 g	1.02 d	1.26 d	0.39 d	0.47 e	0.41 cd	1.93 i	1.51 c	1.70 bc	1.73 c
$P_{60}K_{60}$	0.65 d	0.88 g	1.08 i	1.10 f	1.29 d	0.43 ef	0.47 e	0.41 c	1.81 g	1.52 c	1.77 d	1.78 ef
$P_{60}K_{120}$	0.62 b	0.71 b	0.93 e	0.95 c	1.34 e	0.43 f	0.49 f	0.43 e	1.95 j	1.46 b	1.72 c	1.73 c
$P_{120}K_{60}$	0.73 g	0.79 f	1.09 i	1.06 e	1.33 e	0.38 d	0.53 g	0.49 g	1.85 h	1.53 c	1.80 e	1.76 de
$P_{120}K_{120}$	0.69 e	0.77 d	0.87 c	1.05 e	1.22 c	0.36 cd	0.37 a	0.31 a	1.85 h	1.59 d	1.71 bc	1.60 a
$P_{180}K_{60}$	0.70 f	0.76 cd	0.98 f	1.17 i	1.39 f	0.39 de	0.46 e	0.43 e	1.76 f	1.69 e	1.69 b	1.79 f
$P_{180}K_{120}$	0.78 h	0.76 cd	1.05 h	1.14 h	1.38 f	0.33 ab	0.38 a	0.38 b	2.12 k	1.44 ab	1.77d	1.86 g

**Credibility of differences between column values (nitrogen variants) is expressed by different letters.*

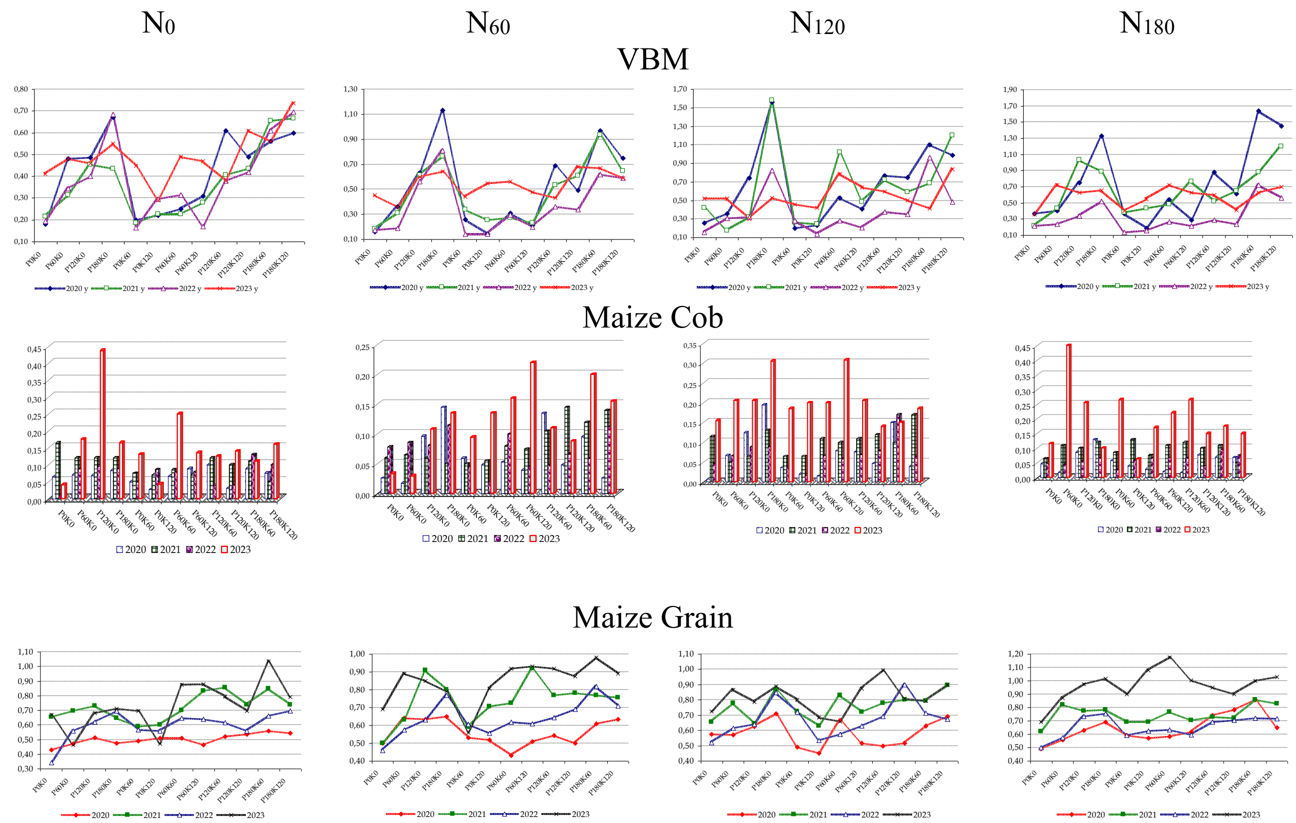

Figure 3. Phosphorus content in the aboveground biomass of maize, depending on NPK norms and ratios by year of study (P_2O_5 %)

During the conditions of 2022, phosphorus concentrations in vegetative biomass were the lowest for all nitrogen fertilizer norms compared to the other study years. Annual phosphorus fertilization at 120 and 180 kg N/ha increased phosphorus concentrations in vegetative biomass. Unlike nitrogen concentration (N%), the extreme drought in 2023 did not significantly increase P_2O_5 % in this organ. Similar trends were observed for phosphorus concentration in the cob, but at significantly lower levels than those in vegetative biomass. Regardless of PK fertilization levels, the cob had the lowest phosphorus content (P_2O_5%) with systematic nitrogen fertilization at 60 kg N/ha. Under extreme drought conditions in 2023, phosphorus content increased at all nutrient levels compared to previous years.

Within each study year, differentiation in phosphorus concentration in the grain was well expressed. In the absence of nitrogen fertilization, phosphorus concentration (P_2O_5%) varied from 0.34% (2022 in $N_0P_0K_0$) to 1.035% (2023 in $N_0P_{180}K_{60}$). The highest average phosphorus concentration in the grain was observed in 2023 (0.730% P_2O_5), and the lowest in 2020 (0.502% P_2O_5). Increasing nitrogen fertilization norms increased phosphorus concentration in the grain, maintaining a high level of differentiation between PK combinations. It can be said that average phosphorus concentrations in the grain at nitrogen fertilization norms of 60 and 120 kg N/ha did not differ significantly. Annual fertilization with 180 kg N/ha in 2023 increased phosphorus content in the grain to 0.966% P_2O_5 compared to the results from previous years.

The average phosphorus concentrations over the study period confirmed the high level of differentiation between PK combinations at all nitrogen fertilization levels in the studied maize organs (Table 4). Despite the clear differentiation between PK fertilizer combinations, the control treatments (without nitrogen fertilization) had the lowest average phosphorus concentrations in all studied organs. Increasing nitrogen fertilization norms led to a significant increase in phosphorus concentrations in vegetative biomass and grain, with less pronounced differentiation in the cob. Unlike the present study, Nenova et al. (2019) reported higher macronutrient content in VBM in the control treatments compared to the fertilized variants they tested.

The average phosphorus content in the cob is lower in the fertilizer combinations with 60 kg N/ha (0.086% P_2O_5). In this group, the highest concentration is observed in the $N_{60}P_{180}K_{60}$ variant -0.119%. In the other nitrogen fertilization groups, the variations in the average values are insignificant, but the differentiation depending on the combinations with phosphorus and potassium is well expressed. In the N_0 group, the average value of % P_2O_5 in the cob is 0.111%, with the maximum observed in the $N_0P_{120}K_0$ variant - 0.218%. The average phosphorus concentrations in the cob for nitrogen fertilization with 120 and 180 kg N/ha are 0.112 and 0.103% P_2O_5, respectively. The maximum concentration in each of these nitrogen groups is achieved by combining with the individual application of phosphorus.

Contrary to many beliefs, maize is sensitive to phosphorus nutrition and requires phosphorus fertilization (Nagy, 2006). The results of the study show that the phosphorus concentration in the grain gradually increases with the nitrogen fertilization norm – from 0.637% P_2O_5 (N_0) to 0.754% P_2O_5 (N_{180}). The fertilizer combinations $N_0P_{180}K_{60}$ (0.776%), $N_{60}P_{180}K_{60}$ (0.795%), and $N_{180}P_{180}K_{60}$ (0.860%) reach their maximum in the respective nitrogen fertilizer groups. With long-term application of the optimal nitrogen fertilization norm for the region (N_{120}), these values are achieved with nitrogen-phosphorus fertilization without the application of potassium fertilization.

Table 4. Phosphorus content in maize organs depending on nitrogen norm and its combination with PK, averaged for 2020-2023 (P_2O_5 %)

PK variants	VBM				Maize cob				Maize grain			
	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}
P_0K_0	0.250 a	0.244 a	0.339 c	0.290 a	0.070 ab	0.050 a	0.081 a	0.069 a	0.524 a	0.538 a	0.619 b	0.580 b
$P_{60}K_0$	0.405 d	0.304 c	0.341 c	0.449 d	0.113 ab	0.050 a	0.097 b	0.156 h	0.548 a	0.684 d	0.708 d	0.553 a
$P_{120}K_0$	0.450 e	0.601 g	0.420 d	0.686 h	0.181 b	0.086 c	0.121 c	0.124 fg	0.636 c	0.756 f	0.674 c	0.605 c
$P_{180}K_0$	0.585 g	0.836 j	1.124 k	0.849 i	0.114 ab	0.111 ef	0.180 e	0.104 de	0.631 c	0.753 f	0.829 h	0.626 d
P_0K_{60}	0.250 a	0.295 c	0.303 b	0.321 b	0.076 ab	0.062 ab	0.081 a	0.109 e	0.585 b	0.571 b	0.684 c	0.586 b
P_0K_{120}	0.258 a	0.271 b	0.258 a	0.333 c	0.056 a	0.065 b	0.076 a	0.073 ab	0.535 a	0.646 c	0.575 a	0.578 b
$P_{60}K_{60}$	0.320 c	0.360 d	0.655 h	0.503 f	0.120 ab	0.098 cde	0.098 b	0.085 bc	0.683 d	0.674 d	0.683 c	0.628 d
$P_{60}K_{120}$	0.308 b	0.280 b	0.435 e	0.475 e	0.093 ab	0.095 cd	0.136 d	0.105 de	0.705 d	0.743 f	0.685 c	0.604 c
$P_{120}K_{60}$	0.444 e	0.504 e	0.618 g	0.571 g	0.096 ab	0.100 cde	0.115 c	0.117 ef	0.696 d	0.720 e	0.741 ef	0.634 de
$P_{120}K_{120}$	0.489 f	0.530 f	0.550 f	0.476 e	0.077 ab	0.087c	0.097 b	0.092 cd	0.633 c	0.711 e	0.756 f	0.628 d
$P_{180}K_{60}$	0.596 h	0.799 i	0.791 i	0.968 j	0.110 ab	0.119 f	0.143 d	0.113 ef	0.776 e	0.795 g	0.734 e	0.640 def
$P_{180}K_{120}$	0.674 i	0.644 h	0.879 j	0.979 k	0.096 ab	0.108 def	0.115 c	0.086 bc	0.693 d	0.748 f	0.790 g	0.651 f

**Credibility of differences between column values (nitrogen variants) is expressed by different letters.*

The results thus far suggest that in the pursuit of balanced nutrition for each crop in the respective agroecological region, long-term and in-depth studies are needed to achieve not only agronomically optimal productivity but also the necessary quality. There are many nutrients required to achieve this goal, but the current study is focused on the status of the main macronutrients. Lastly, we will also focus on the potassium concentration in maize organs. For proper growth, development, and achieving sustainable yield, this nutrient is of utmost importance and is an essential characteristic (Randhawa & Arora, 2000; Bukhsh et al., 2012). It has long been known that potassium plays a crucial role in regulating osmotic pressure, the stomata opening and closing mechanism, protein synthesis, photosynthesis, and stimulating dozens of enzymatic reactions (Bukhsh et al., 2009; Akram et al., 2010). Together with phosphorus, it is responsible for energy transfer within plants and the growth and development of the root system. All this makes potassium a key element in increasing the tolerance of plants to stressful situations at different stages of crop development (Kirkby & Römheld, 2009; Marschner, 2012; Ibni et al., 2015; Muhammad, 2020).

In the absence of nitrogen fertilization, the tested PK combinations showed well-expressed differences regarding potassium concentration in vegetative biomass (Fig. 4). This differentiation deepened over the years, especially in the years characterized by drought during the BBCH 50-59 phase (2022 and 2023). The highest values for potassium concentration in vegetative biomass were observed in 2023. The PK fertilizer combinations also influenced the element's values. In 2020, vegetative biomass had the highest K_2O %

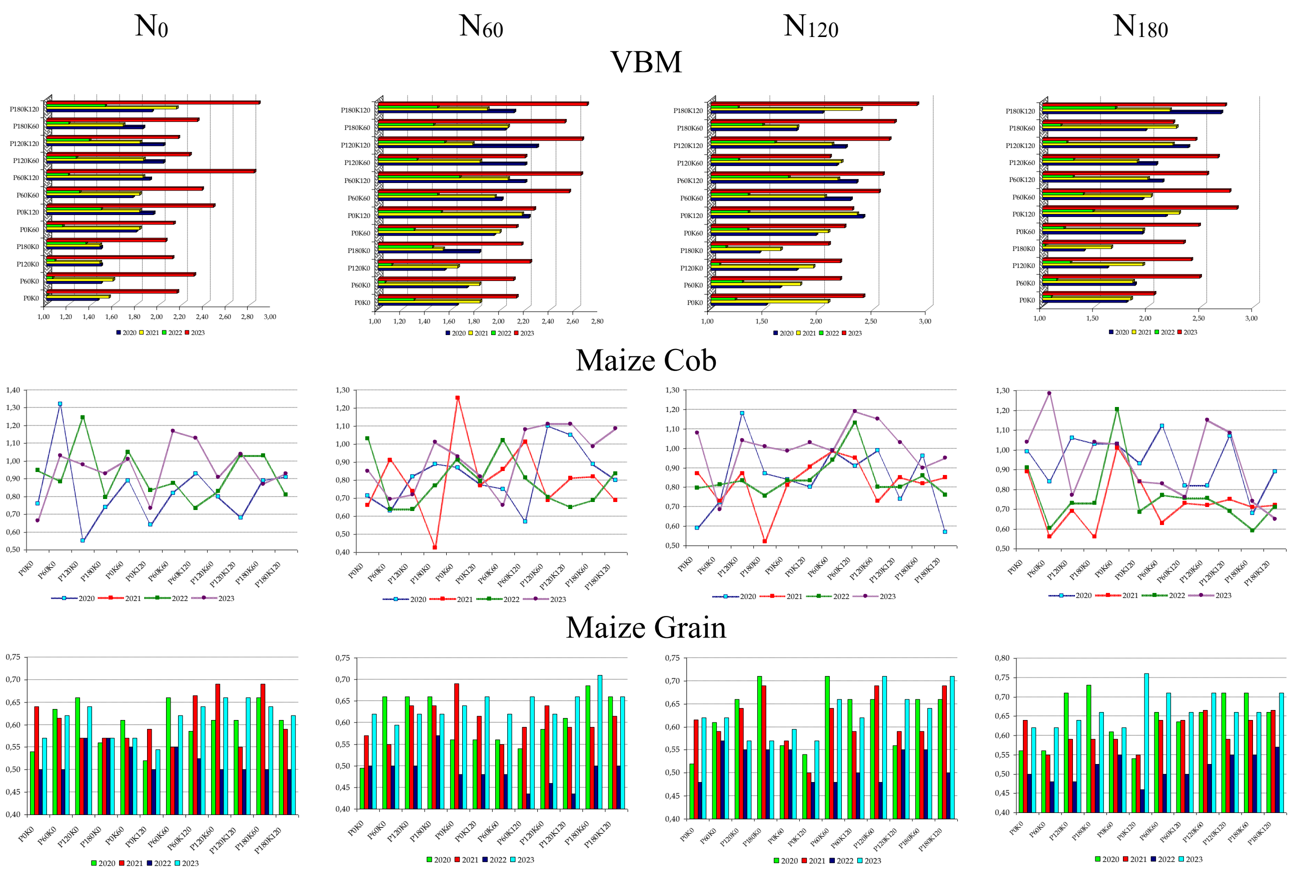

Figure 4. Potassium content in the aboveground biomass of maize depending on NPK norms and ratios by year of study, K_2O %

in the $N_0P_{120}K_{60}$ and $N_0P_{120}K_{120}$ variants (2.030% -Waller-Duncan test - h). Although potassium concentrations varied in the following years, the maximum concentration of this element was achieved in the $N_0P_{180}K_{120}$ variant. This fact clearly indicates the synergy between phosphorus and potassium. Independent potassium fertilization also contributed significantly to increasing potassium concentration in vegetative biomass, especially compared to the control variant – $N_0P_0K_0$.

At the low nitrogen norm (60 kg N/ha), the maximum potassium content in the VBM for each of the years of study was reached in the variant $N_{60}P_{60}K_{120}$. On average for the study period, the potassium concentration in this variant exceeded the same in the case of nitrogen fertilization independently ($N_{60}P_0K_0$) by 24.21%. Conditions in 2021 and 2023 lead to an increase in the average potassium content in VBM, regardless of fertilizer combinations.

In the following years, the most significant impact on potassium concentration in vegetative biomass was seen in variants with different phosphorus and potassium combinations, but always involving potassium from the 120 kg K_2O/ha norm.

Against the background of the optimal nitrogen norm for the region of 120 kg N/ha, an increase in potassium concentration was again observed compared to the nitrogen groups with 0 and 60 kg N/ha, with well-expressed differentiation between the combinations with phosphorus and potassium. The strong influence of the $N_{120}P_0K_{120}$ variant, as well as the combination with phosphorus and potassium - $N_{120}P_{180}K_{120}$, was maintained, although in 2023 the differences were statistically insignificant.

The combinations for the highest tested nitrogen norm of 180 kg N/ha fully confirmed the indicated trends. The year's conditions also strongly influenced the established maximum potassium concentrations in the VBM. In 2021 and 2023, the highest concentrations were observed in the $N_{180}P_0K_{120}$ fertilizer variant - 2.285% and 1.685% K_2O, respectively, while in 2020 and 2023, they were observed in the $N_{180}P_{180}K_{120}$ variant - 2.680% and 2.830% K_2O, respectively.

The potassium concentration in the cob varies depending on the meteorological conditions of the years and the combination of nitrogen, phosphorus, and potassium norms. In the control variant (N_0), potassium concentration is higher in 2021 - $N_0P_{180}K_{120}$ (2.145% K_2O) compared to the other years of the study. The years 2020 and 2022 are characterized by the highest K_2O % in the variants $N_0P_{60}K_0$ and $N_0P_{120}K_0$. For the extremely unfavorable year 2023, similar results were achieved with PK fertilization at norms of 60 kg K_2O/ha or in combination with 120 P_2O_5 kg/ha phosphorus.

Including a low nitrogen norm (60 kg N/ha) definitely increases the potassium content in the cob when phosphorus and potassium are included in the fertilizer norms. In 2020 and 2023, the highest concentrations were reached with fertilization at $N_{60}P_{120}K_{60}$ and $N_{60}P_{120}K_{120}$, while in 2021, it was $N_{60}P_0K_{120}$. Only in 2022 did the individual nitrogen fertilization ($N_{60}P_0K_0$) and balanced input in the $N_{60}P_{60}K_{60}$ variant result in higher potassium concentrations in the cob.

The next increase in the nitrogen norm (120 kg N/ha) also maintains the differentiation across years and fertilizer combinations. In 2020, the maximum was reached in the $N_{120}P_{120}K_0$ variant, while in the other years, it was in the combinations with $P_{60}K_{120}$ and $P_{60}K_{60}$.

Against the background of the highest nitrogen norm, the maximum potassium concentration in the cob was recorded in 2023 – $N_{180}P_{60}K_0$ (1.285% K_2O). In the other years, there was a clear trend of a strongly pronounced positive effect on the potassium concentration in this organ in the $N_{180}P_0K_{60}$ and $N_{180}P_{60}K_{60}$ variants. In this organ, increasing nitrogen norms not only raised the potassium concentration, but also deepened the differentiation between nitrogen combinations with phosphorus and potassium.

The average potassium content in maize grain over the entire study period, under experimental conditions, was 0.595% K_2O. Meteorological conditions had a strong influence on this indicator's values both for individual nitrogen applications and for combining them with phosphorus and potassium. Overall, in 2022, maize grain had the lowest potassium concentration, while in 2023, it had the highest. The tested fertilizer combinations, combined with increasing nitrogen norms, had the most pronounced positive effect on potassium values in the grain in 2020.

In the absence of nitrogen fertilization, combinations with high PK fertilizer norms made a significant contribution to enriching the grain with potassium. As nitrogen fertilization norms increased, PK combinations also had a positive effect on this indicator, with the maximum potassium concentration in the grain (0.76% K_2O) reached in the $N_{180}P_0K_{120}$ variant in 2023.

On average, during the study period, vegetative biomass consistently had over 2% K_2O when combining the tested nitrogen norms with $P_{180}K_{120}$ (Table 5).

Fertilization with 60, 120, and 180 kg N/ha increases the number of variants with similar results, including the use of potassium fertilization at 120 kg K_2O/ha, as well as its combination with increasing phosphorus fertilization norms.

The highest average potassium values in the cob were obtained with fertilizer combinations that did not include nitrogen. Increasing nitrogen fertilization norms led to a decrease in potassium concentration in this organ. The highest values for K_2O% were found in the $N_{60}P_0K_{60}$ (0.99%) and $N_{180}P_0K_{60}$ (1.07%) variants, and with fertilization at 120 kg N/ha, this was the case for the $N_{120}P_{60}K_{120}$ variant (1.05%).

On average for the period, the potassium content in the grain showed less variation depending on the type of PK fertilization combined with the tested nitrogen norms, compared to the vegetative biomass (VB) and the cob. When combining nitrogen norms of 0, 60, and 180 kg N/ha with $P_{180}K_{60}$ and $P_{180}K_{120}$, the maize grain had higher potassium content compared to the respective control variants. A similar effect was observed with phosphorus-only fertilization when combined with nitrogen norms of 60 and 120 kg N/ha. The comprehensive study by Celik et al. (2010) provides information on the maximum concentration of NPK in some maize organs. The authors indicate that increased potassium fertilization norms contribute to higher protein, crude starch, and oil content in maize grain.

The average values for nitrogen concentration in maize organs, depending on nitrogen fertilization levels, were highest under water-temperature stress conditions, which started before the reproductive organs appeared (2023) (Table 6). The study years were maximally differentiated

Table 5. Potassium content in maize organs depending on nitrogen norm and its combination with PK combinations, averaged for 2020-2023, K_2O%

PK variants	VBM				Maize cob				Maize grain			
	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}	N_0	N_{60}	N_{120}	N_{180}
P_0K_0	1.52 a	1.72 c	1.80 bc	1.69 b	0.82 b	0.81 d	0.83 c	0.96 h	0.56 b	0.546 a	0.56 b	0.58 b
$P_{60}K_0$	1.60 d	1.67 b	1.74 b	1.83 d	1.01 i	0.72 a	0.74 a	0.82 d	0.59 de	0.576 bc	0.60 cd	0.55 a
$P_{120}K_0$	1.53 b	1.63 a	1.75 b	1.80 c	0.91 g	0.73 a	0.98 g	0.81 d	0.61 fgh	0.61 de	0.61 de	0.61 c
$P_{180}K_0$	1.59 c	1.74 d	1.58 a	1.60 a	0.82 b	0.77b	0.79 b	0.84 e	0.57 bc	0.623 f	0.63 fg	0.63 d
P_0K_{60}	1.72 e	1.83 e	1.91 cd	1.89 e	0.93 h	0.99 h	0.87 d	1.07 i	0.58 bc	0.59 cd	0.57 b	0.59 b
P_0K_{120}	1.93 i	2.04 i	2.10 e	2.19 k	0.73 a	0.79 c	0.89 e	0.82 d	0.54 a	0.58 bc	0.52 a	0.58 b
$P_{60}K_{60}$	1.81 g	1.99 g	2.06 de	2.03 i	0.88 de	0.82 d	0.98 g	0.84 e	0.60 def	0.55a	0.62 f	0.63 d
$P_{60}K_{120}$	1.95 j	2.14 k	2.20 e	1.99 h	0.90 fg	0.87 f	1.05 h	0.77 c	0.60 efg	0.56 a	0.59 c	0.60 c
$P_{120}K_{60}$	1.85 h	1.88 f	1.93 cd	1.98 g	0.85 c	0.90 g	0.92 f	0.86 f	0.62 gh	0.58bc	0.64 g	0.63 de
$P_{120}K_{120}$	1.85 h	2.06 j	2.15 e	2.07 j	0.89 ef	0.91 g	0.86 d	0.90 g	0.58 cd	0.57 b	0.59 c	0.63 d
$P_{180}K_{60}$	1.76 f	2.01 h	1.94 cd	1.91 f	0.92 h	0.85 e	0.89 e	0.68 a	0.62 h	0.62 ef	0.61 e	0.64 def
$P_{180}K_{120}$	2.12 k	2.04 i	2.14 e	2.32 l	0.87 d	0.85 e	0.78 b	0.74 b	0.58 cd	0.61 def	0.64 g	0.65 f

**Credibility of differences between column values (nitrogen variants) is expressed by different letters.*

based on nitrogen content in VB and grain for each tested nitrogen norm. Nenova et al. (2019) found that the nitrogen, phosphorus, and potassium content in maize grain were significantly influenced by the year of the experiment. Except for the fertilization variant with 180 kg N/ha, in the other nitrogen fertilization variants, nitrogen concentration in the cob was less differentiated.

Table 6. Average nitrogen (N%), phosphorus (P_2O_5%), and potassium (K_2O%) content in maize organs by year and nitrogen norm groups, combined with PK fertilization

Nitrogen Norms, kg/ha	Macro-Elements, %	2020	2021	2022	2023
VBM					
N_0	N	0.404 a	0.492 b	0.403 a	1.318 c
	P_2O_5	0.421 c	0.375 a	0.390 b	0.490 d
	K_2O	1.761 c	1.740 b	1.236 a	2.335 d
N_{60}	N	0.663 c	0.656 b	0.563 a	1.262 d
	P_2O_5	0.508 c	0.475 b	0.368 a	0.538 d
	K_2O	1.973 c	1.874 b	1.385 a	2.351 d
N_{120}	N	0.927 c	0.847 b	0.738 a	1.294 d
	P_2O_5	0.658 d	0.643 c	0.392 a	0.545 b
	K_2O	1.967 b	2.053 c	1.338 a	2.403 d
N_{180}	N	1.207 c	0.847 b	0.819 a	1.400 d
	P_2O_5	0.786 d	0.676 c	0.360 a	0.599 b
	K_2O	2.046 c	2.036 b	1.342 a	2.502 d
Maize cob					
N_0	N	0.306 b	0.304 b	0.278 a	0.741 c
	P_2O_5	0.068 a	0.100 a	0.073 a	0.159 b
	K_2O	0.828 b	0.806 a	0.923 c	0.950 d
N_{60}	N	0.277 b	0.260 a	0.319 c	0.653 d
	P_2O_5	0.066 a	0.084 b	0.071 a	0.122 c
	K_2O	0.822 c	0.803 b	0.792 a	0.921 d
N_{120}	N	0.280 a	0.283 a	0.330 b	0.911 c
	P_2O_5	0.072 a	0.100 b	0.071 a	0.204 c
	K_2O	0.847 b	0.824 a	0.847 b	10.003 c
N_{180}	N	0.307 b	0.270 a	0.314 c	0.854 d
	P_2O_5	0.058 a	0.100 b	0.062 a	0.199 c
	K_2O	0.938 d	0.743 a	0.764 b	0.927 c
Maize grain					
N_0	N	0.998 a	1.083 b	1.140 c	1.801 d
	P_2O_5	0.502 a	0.720 c	0.596 b	0.730 c
	K_2O	0.605 b	0.608 b	0.522 a	0.613 b
N_{60}	N	1.439 b	1.349 a	1.538 c	1.879 d
	P_2O_5	0.559 a	0.738 c	0.641 b	0.842 d
	K_2O	0.603 b	0.607 b	0.487 a	0.640 c
N_{120}	N	1.761 c	1.489 a	1.638 b	2.047 d
	P_2O_5	0.578 a	0.760 c	0.672 b	0.815 d
	K_2O	0.626 c	0.616 b	0.520 a	0.629 c
N_{180}	N	1.854 c	1.402 a	1.682 b	2.157 d
	P_2O_5	0.651 a	0.754 c	0.663 b	0.967 d
	K_2O	0.649 c	0.619 b	0.513 a	0.669 d

**Credibility of differences between column values (nitrogen variants) is expressed by different letters.*

These trends largely apply to phosphorus concentration in maize organs. Uniformity in crop response across years at a single fertilizer level was observed in the cob, which is why the Waller-Duncan test classified them in the same group. This also applies to phosphorus concentration in the grain under the variant reflecting the natural fertility of the experimental plot.

Potassium concentration by organ, especially in VBM and the cob, also statistically significantly differentiated the study years. The lowest average potassium values by fertilizer norms and years were observed in the grain. In this organ, the values of the indicator were less differentiated by year, except for variants fertilized with 180 kg N/ha.

The results, summarized in this way, through the study of changes in NPK concentration in maize organs, clearly show the effect of the tested fertilizer variants on the internal mechanism of the nutrient regime's impact. In their study, Huh et al. (2010) found that fertilization with different combinations (NP, NK, PK, NPK) led to changes in several macro- and micronutrients compared to the control variant. The authors note that there are changes in the degree of reaction and ranking of fertilizer variants in the tested organs. The research by Bojtor et al. (2022) found that maize grain had the highest nitrogen/protein content when nitrogen was applied at 120 kg/ha, and higher nitrogen norms had no significant effect on this trait. Overall, to achieve maximum yield quantity and quality, the authors recommend combining nitrogen fertilization with PK fertilizers when growing maize.

On average for the experiment, it was found that increasing nitrogen norms increased the concentration of nitrogen and phosphorus in vegetative biomass (VBM) and grain, as well as potassium in VBM (Fig. 5). The cob is poorer in nitrogen and phosphorus compared to the other organs. In terms of potassium concentration, it surpasses the grain but falls short of VBM. From the perspective of nitrogen fertilization norms, potassium concentration in the grain and cob shows less pronounced dynamics.

The cob also exhibits weaker dynamics regarding phosphorus concentration. Increasing phosphorus norms in combination with nitrogen (NP variants) significantly raised nitrogen concentra-

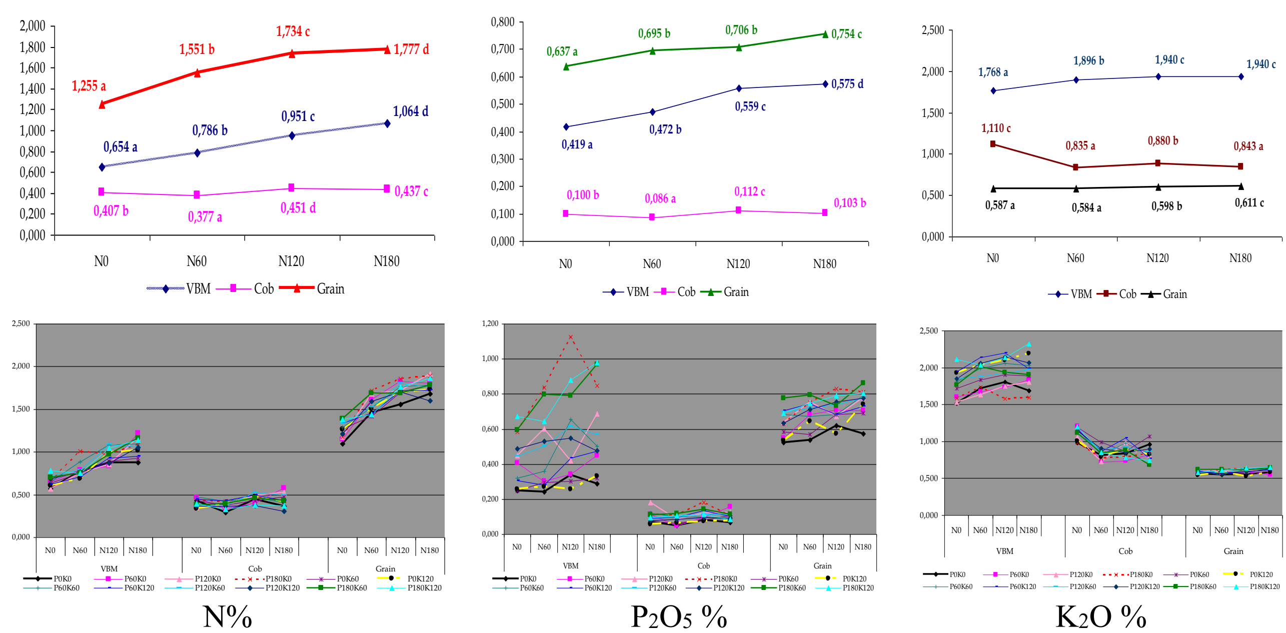

Figure 5. Average values for the concentration of macronutrients depending on nitrogen fertilization level and PK combinations for each organ, %

tion above the control variants in all organs. Nitrogen-potassium combinations also contributed to increasing these values, but compared to NP, the effect was less pronounced. Combinations of all three macronutrients contributed to the maximum increase in nitrogen concentration in VBM at $P_{120}K_{60}$ and $P_{180}K_{120}$, and in the grain at $P_{180}K_{60}$. The average values of these combinations nearly matched those of NP and NK and exceeded the average control values by about 30%. The nitrogen concentration in grain was most significantly influenced by NP fertilization, where the increase over the control average was 12.43%. Nitrogen concentration in grain was also positively influenced by NK and NPK combinations, but under the experimental conditions, these combinations were inferior to NP combinations.

In the cob, all combinations contributed to increasing the nitrogen concentration in this organ compared to the control, but the differences between NP, NK, and NPK combinations were insignificant.

The NP and NPK combinations led to a more pronounced increase in nitrogen in maize grain compared to the NK combinations. The increase compared to the average nitrogen control was 11.2%.

The phosphorus concentration in VBM under NK combinations was practically equal to the average control formed by the individual nitrogen fertilization norms. NP and NPK combinations increased phosphorus content in the non-economic parts of the crop by more than 2 times. The highest increase in this indicator was observed under NP with a phosphorus norm of 180 kg P_2O_5 /ha - 3 times higher, while under NPK variants, it was under $P_{180}K_{120}$ - 2.83 times higher.

An increase in phosphorus in the cob was observed under all NPK combinations, with the weakest increase under NK combinations. The highest increase compared to the control was under NP and NPK combinations - 2.29 times higher.

A similar trend was seen in phosphorus concentration in the grain. The increase compared to the control was as follows: 1.31 times under NPK variants, 1.26 times under NP, and 1.12 times under NK. The maximum was observed under $P_{180}K_{60}$, with a 40.25% increase over the control.

The average potassium content in VB for the entire experiment was 1.87% K_2O. The NP combination variants were at the control level, while under NK and NPK combinations, the potassium concentration in VB increased by 1.15 and 1.19 times, respectively. The maximum was reached under $P_{180}K_{120}$ - 2.10% K_2O, representing a 25.0% increase over the control.

The average potassium concentration in the cob was 0.917% K_2O. The maximum concentration was reached under P_0K_{60} - 1.03% K_2O. NP and NPK combinations did not significantly affect this indicator and remained at the control level.

Despite the year-on-year dynamics, the average potassium values in grain under NP, NK, and NPK combinations did not show significant differences. A slight increase was observed in the NPK group, where the $P_{180}K_{120}$ variants had the highest potassium concentration in grain—0.651% K_2O, compared to 0.580% K_2O for the control.

The concentration of macronutrients by growth phases, as well as in the final phase of maize development, is a product of the crop's growth conditions (Gnanasundari et al., 2018). The complex interactions between NPK have been the subject of numerous studies, where it has been found that their presence in fertilizer norms not only enhances their uptake but also that of many other elements. Clearly positive relationships between them have also been established, confirmed by high correlation coefficient values (Thippeswamy, 1995; Kumawat, 2014; Kumar et al., 2015).

As a result of the study, a strongly expressed correlation between nitrogen concentration in the grain and that in VBM was found (Table 7). This correlation was most pronounced in the control variant, reflecting the natural fertility of the experimental plot.

Increasing nitrogen norms lead to a decrease in correlation values, but they remain at sufficiently high levels. A similar trend is observed in the relationship between nitrogen in the grain and potassium content in VB, again particularly pronounced under conditions without nitrogen fertil-

Table 7. Correlation dependencies between NPK content in maize grain and those in vegetative biomass and cob, averaged for the period 2020-2023

N fertilization Norms, kg/ha	VBM			Maize Cob		
	N	P	K	N	P	K
Grain N%						
N_0	0.926(**)	0.305(**)	0.706(**)	0.797(**)	0.347(**)	0.272(**)
N_{60}	0.636(**)	0.386(**)	0.319(**)	0.697(**)	0.432(**)	0.070^{ns}
N_{120}	0.734(**)	0.245(*)	0.345(**)	0.730(**)	0.645(**)	0.427(**)
N_{180}	0.741(**)	0.153^{ns}	0.355(**)	0.723(**)	0.443(**)	0.282(**)
Grain P_2O_5%						
N_0	0.483(**)	0.342(**)	0.405(**)	0.360(**)	0.350(**)	0.126^{ns}
N_{60}	0.478(**)	0.405(**)	0.395(**)	0.576(**)	0.514(**)	0.084^{ns}
N_{120}	0.420(**)	0.363(**)	0.227(*)	0.452(**)	0.621(**)	0.133^{ns}
N_{180}	0.529(**)	0.320(**)	0.645(**)	0.633(**)	0.584(**)	-0.088^{ns}
Grain K_2O%						
N_0	0.282(**)	0.232(*)	0.495(**)	0.352(**)	0.380(**)	0.274(**)
N_{60}	0.466(**)	0.548(**)	0.647(**)	0.352(**)	0.380(**)	0.274(**)
N_{120}	0.503(**)	0.634(**)	0.520(**)	0.194^{ns}	0.392(**)	0.168^{ns}
N_{180}	0.589(**)	0.591(**)	0.704(**)	0.311(**)	0.308(**)	0.274(**)

ization. High values are found for the coefficients reflecting the correlation between nitrogen in the grain and phosphorus and potassium content in the cob.

The phosphorus and potassium content in the grain is characterized by positive relationships with NPK concentrations in VB and the cob. The strongest relationships are with potassium in VB (0.645**) under N_{180} and with NP in the cob, respectively 0.633** and 0.584**, again under N_{180} fertilization.

The concentration of potassium in maize grain is positively correlated with NP concentration in VB, strengthening with increasing nitrogen fertilization norms. Positive, but not significantly strong, correlations are found with NPK concentrations in the cob.

On average for the period, correlations were also established between nitrogen, phosphorus, and potassium concentrations in different organs depending on nitrogen fertilization levels (Fig. 6). High correlation dependencies between N-K in VB are clearly confirmed with increasing nitrogen fertilization norms. The only insignificant relationship is between P-K under 120 kg N/ha fertilization.

In the cob, the N-P relationships (N_{60}, N_{120}, N_{180}) are most pronounced, where the correlation values increase from 0.61** to 0.86**. In the grain, the strongest correlation is between N-P in the variant without nitrogen fertilization (0.60**). All other correlations are positive but below this level.

CONCLUSIONS

The annual accumulation of nutrients in soil through mineral fertilization with different norms and ratios between nitrogen, phosphorus and potassium from 1967 to the present leads to significant dynamics in the concentration of macronutrients by organs in the final stage of maize development during the time period of the present study (2020-2023).

The direction of reaction and the degree of distribution of different elements across various fertilizer combinations show clear differen-

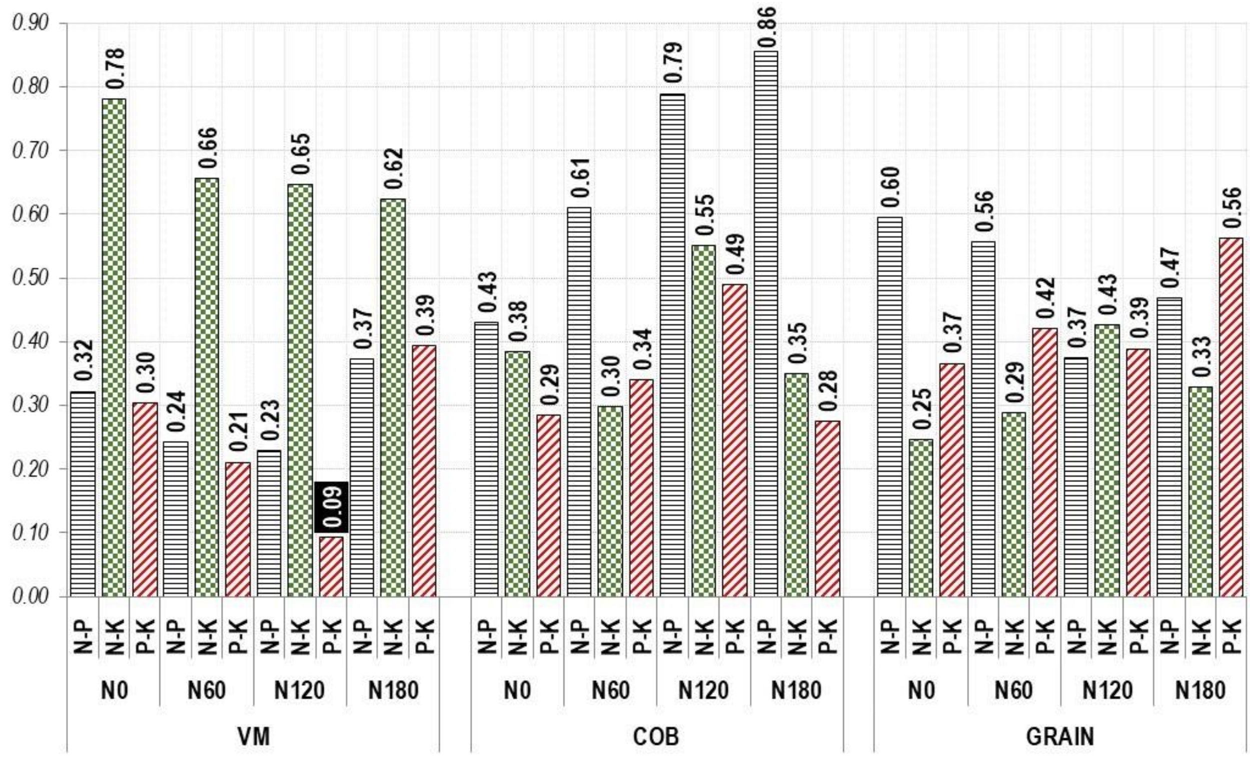

Figure 6. Correlations between the NPK content of the different organs of maize, according to the nitrogen norms, averaged over the period 2020-2023

tiation but also some similarity or uniformity. It was found that the nitrogen content in maize grain increases with increasing nitrogen fertilization norms across all phosphorus and potassium combinations (from 1.26% to 1.77%). A similar trend was observed for nitrogen concentration in vegetative biomass (leaves + stems) – from 0.65% to 1.07%. The phosphorus concentration in grain also increases with higher nitrogen fertilization, although the trend is less pronounced. The influence of nitrogen norm and its combination with PK on the chemical composition of the cob is the least pronounced.

The highest potassium concentration was found in vegetation biomass, followed by that in the cob and grain. Compared to the dynamics of nitrogen and phosphorus concentration, depending on increasing nitrogen fertilization and its combination with PK, the potassium concentration is the least pronounced.

It is undeniable that such prolonged agricultural intensification is a good example of how plants react and what the relationships are between the different organs. The results show that the macronutrient content in the grain is highly correlated with that in the vegetative biomass, as well as with nitrogen in the cob.

Acknowledgements

The present research was reported at an jubilee scientific conference with international participation “Sustainable and competitive agriculture under the conditions of global climate change“, held in September, 03-04 2024, in Maize Research Institute, Knezha, Bulgaria.

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Received: February, 06, 2025; Approved: March, 25, 2025; Published: June, 2025