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The Delayed Effect of Low-Energy Lignite Organic Matter on the Treatment Optimization of *Zea mays* L. Grown for Silage

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Abstract: The field experiment was conducted in the central-eastern Poland. The aim of the research was to determine the effect of low-energy lignite organic matter applied to the preceding crop in the form of an organomineral fertilizer on the treatment optimization of *Zea mays* L. maize grown for silage. Two factors were taken into account in the research: factor I—five fertilization plots control plot—without fertilization (1), NPKMgS (2), NPKMgS + N1(3), NPKMgS + N2 (4), NPKMgS + N3 (5); factor II—three varieties of *Zea mays* L. Nitrogen was applied as fertilizers 3, 4 and 5 at doses of N1-20, N2-40 and N3-60 kg per hectare. In the spring each year, selected plots were pre-sown with mineral fertilizers at doses of 100 kg·N, 35 kg·P, 125 kg·K, 12 kg·Mg and 14 kg·S per hectare. Organomineral fertilizer based on low-energy lignite was applied to the preceding crop (maize grown for silage) on two plots, in 1 and 5 t·ha^{−1} doses. Mineral fertilizers used in research significantly reduced the content of nitrogen, phosphorus, potassium, magnesium and sulphur in the dry matter of plants. The uptake of the nutrients reached the highest values for maize treated with NPKMgS + N1, NPKMgS + N2 and NPKMgS + N3. The agronomic efficiency (AE) of nitrogen, phosphorus, potassium, magnesium and sulphur, all of which were applied in the form of the polyfoska[®] fertilizer, M-MAKS (NPKMgS), potassium salt and urea, reached the highest values for plots treated with NPKMgS + N1 and NPKMgS + N2. In turn, the treatment of NPKMgS and NPKMgS + N3 with nitrogen, phosphorus, potassium, magnesium and sulphur resulted in the highest values of physiological efficiency (PE). Based on the three-year research carried out with the use of polyfoska[®] M-MAKS (NPKMgS), potassium salt and urea in the fertilization of maize grown for silage, it is possible to recommend the optimal dose of NPKMgS + N1 mineral fertilizers (100-35-125-12-14 pre-sowing, 20 kg top dressing N) and NPKMgS + N2 (pre-sowing 100-35-125-12-14, top dressing 40 kg·N). The low-energy lignite applied to the preceding crop in doses of 1 t and 5 t at the NPKMgS + N1 and NPKMgS + N2 plots contributed to the achievement of the analyzed parameters (uptake, AE and AE) at a high level.

Keywords: low-energy lignite (reusable organic additives); bioavailability; maize; fertilization with NPKMgS; fertilization efficiency



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1. Introduction

Maize belongs to plants of very high economic importance. It can be grown for grain, but it is also a silage crop, and recently it has been used for the production of biofuel (ethanol and biogas). The plant effectively uses nitrogen from fertilizers, with adequate doses of phosphorus, potassium and magnesium, and from soil [1,2]. The fertilizer treatment of maize for silage should lead to high nutrient efficiency. The availability of nutrients in soil is a key factor influencing the content of nutrients in maize and yields [3,4]. Maize responds well to NPK fertilisation, producing the highest biomass of all crops with a higher content of nutrients [5]. With the optimal levels of absorbable forms of nutrients in the soil, slow-release fertilizers ensure proper nutrition of maize without a negative impact on the soil environment and groundwater [6]. Based on lignite waste, an organomineral fertilizer

applied to the preceding crop meets those requirements. This way, significant amounts of absorbable components are introduced into the soil, entering the sorption complex or bounding into organomineral compounds (chelates). To obtain high yields, maize grown for silage requires an increased uptake of nitrogen, potassium, phosphorus, magnesium and sulphur [7,8].

The organomineral fertilizer based on lignite waste applied to the preceding crop indirectly affects phosphorus content in soil solution. Humic and fulvic acids from lignite increase the chelation of Ca^{2+} , Mg^{2+} , Al^{3+} and Fe^{3+} ions. This prevents the precipitation of phosphates and increases the availability of phosphorus to plants [9]. According to some studies [10], increasing nitrogen doses (80, 120, 160 $\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$) and the localized application of an NPS (M) granular fertilizer together with seeds increase maize nitrogen and phosphorus content. Potassium is an element taken up by maize in large quantities [11]. The limited application of potassium (65 $\text{kg}\cdot\text{K}\cdot\text{ha}^{-1}$) in conditions of very high abundance in the soil in its absorbable form (over 250 $\text{mg}\cdot\text{K}\cdot\text{kg}^{-1}$) has little effect on the change in the optimal nitrogen and phosphorus content in maize [12–14]. Nitrogen and phosphorus concentrations in plants do not affect potassium content [15]. According to some field experiments, the efficiency of mineral potassium is lower than the efficiency of nitrogen and phosphorus. Many studies [12,16,17] have reported a release of non-exchangeable potassium into soil solutions under the influence of Ca^{2+} and Mg^{2+} ions.

The application of organic materials to maize increases sulphur content in its biomass and in the soil [18]. Humus contained in the soil in sufficient quantities has a positive effect on nitrogen efficiency [19,20]. Research on the quality and quantity of organic matter should be the foundation of the general evaluation of soil quality and its productive potential [21,22]. Additionally, an adequate supply of mineral sulphur to the soil affects the yield-increasing effect of nitrogen [23]. The optimal timing of nitrogen application and divided doses during the period of intensive growth of maize cultivated for silage increase the efficiency of nitrogen fertilizer [24–26]. Phosphorus used in optimal doses eliminates the effects of excessive amounts of nitrogen and increases its effectiveness [27–29]. The high efficiency of sulphur application was achieved with an N:S ratio of 10:1 in plants [27,30–32].

A research hypothesis suggested that an organomineral fertilizer produced on the basis of lignite waste and applied to the preceding crop may increase agronomic and physiological efficiency. The aim of the research was to determine the long-term effect of lignite waste applied to the preceding crop in the form of an organomineral and mineral fertilizer on the optimization of the treatment of maize (*Zea mays* L.) grown for silage.

2. Materials and Methods

2.1. Experimental Site and Treatments

Field experiments were conducted (2014–2016) at the Siedlce University of Natural Sciences and Humanities on the fields of the Agricultural Experimental Station—Zawady (52°03' N 22°33') east-central Poland. They were conducted using a split-plot block with two research factors with three replications. All plot sizes were 15 m^2 . The first factor was established as a five fertilizer combination (control—no fertilization (1), NPKMgS (2), NPKMgS + N1 (3), NPKMgS + N2 (4) and NPKMgS + N3 (5)), but the second factor was characterized as three cultivars of maize: Silien (FAO 220), P8000 (FAO 230) and PR 38A79 (FAO 270). Mineral fertilizers was applied before sowing maize at the following doses: 100 $\text{kg}\cdot\text{N}$, 35 $\text{kg}\cdot\text{P}$, 125 $\text{kg}\cdot\text{K}$, 12 $\text{kg}\cdot\text{Mg}$ and 14 $\text{kg}\cdot\text{S}$ per hectare in the form polyfoska® M-MAKS (NPKMgS), potassium salt 60% K_2O and urea 46% N. Nitrogen was applied as top dressing with 3, 4 and 5 fertilizer combinations at doses of 20, 40 and 60 $\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$ in the form urea 46% N. The chemical compounds of polyfoska® M-MAKS (NPKMgS) are $\text{NH}_4\text{H}_2\text{PO}_4$, $(\text{NH}_4)_2\text{HPO}_4$, KCl, MgCO_3 and K_2SO_4 . The organomineral fertilizer (Figure 1) based on lignite waste produced by the company INCO (Warsaw, Poland) was applied to the preceding crop (maize grown for silage) in two doses (1 and 5 $\text{t}\cdot\text{ha}^{-1}$). In the three consecutive years of research, the test plant was maize grown for silage.



Figure 1. Organomineral fertilizer applied to the preceding crop (maize grown for silage).

The field experiments were conducted on *Albic Luvisol (Arenic)* according to the IUSS World Reference of Soil Resources [33]. All cultivation and harvest practices were carried out in accordance with agricultural requirements for maize.

2.2. Soil and Plant Sampling and Analysis

Soil samples were collected before establishing the experiment at a depth of 0–30 cm. Soil pH was determined with the potentiometric method in 1 mol dm^{−3} KCl. The air-dry soil to solution ratio was 1:2.5 (*m/v*). Total carbon and nitrogen content in the soil and plant was determined with a Perkin Elmer (Waltham, MA, USA) CHNS/O 2400 auto analyzer coupled with a thermal conductivity detector (TCD) and by using acetanilide as the reference material. The content of available phosphorus and potassium in the soil was determined with the Egner–Riehm method DL [34,35], while magnesium was measured using the Schatschabel method [36]. The dry matter (DM at 105 °C) was determined in all samples of the test plants. The content of available and total forms of P, K, Mg and S in the soil and plants was determined using the ICP-AES method, with an inductively excited plasma atomic emission spectrometer (optima 3200RL, Perkin Elmer, Waltham, MA, USA).

The uptake of N, P, K, Mg and S by maize grown for silage was calculated using the yield and concentrations of nutrients. Agronomic efficiency (AE) was calculated according to the following formula according to Rathke et al. [37].

$$AE = Y_i - Y_0 / N_i (P_i, K_i, Mg_i, S_i) \quad (1)$$

where: Y_i —yield at *i* level of fertilizer (*i* = NPKMgS, NPKMgS + N1,

NPKMgS + N2, NPKMgS + N3) (kg·ha^{−1});

Y_0 —yield at 0 level of fertilizer;

N_i (P_i , K_i , Mg_i and S_i)—level of fertilizer;

AE—agronomic efficiency (kg·kg^{−1}).

Physiological efficiency (PE) was calculated according to the following formula (Rathke et al. [37]):

$$PE = Y_i - Y_0 / U_{Pi} - U_{P0} \quad (2)$$

where: Y_i —yield at *i* level of fertilizer (*i* = NPK, NPKMgS, NPKMgS + N1,

NPKMgS + N2, NPKMgS + N3);

Y_0 —yield at 0 level of fertilizer;

U_{Pi} —uptake at N_i , P_i , K_i , Mg_i and S_i level of fertilizer;

U_{P0} —uptake at N_0 , P_0 , K_0 , Mg_0 and S_0 level of fertilizer;

PE—physiological efficiency (kg·kg^{−1}).

2.3. Weather Conditions

Data on hydrological and meteorological conditions were provided by the Institute of Meteorology and Water Management in Warsaw, the Hydrological and Meteorological Station in Siedlce (Tables 1 and 2). The hydrothermal coefficient (K) for individual years, according to Sielanianov's index, is shown in Table 2 [38]. The following formula was applied:

$$K = (Mo \cdot 10) / (Dt \cdot \text{days}) \quad (3)$$

where: K—hydrothermal coefficient for individual months;

Mo—total monthly precipitation;

Dt—mean daily temperatures in a particular month.

Table 1. Characteristics of hydrothermal conditions, on the basis of data provided by the Institute of Meteorology and Water Management in Warsaw, the Hydrological and Meteorological Station in Siedlce (Poland).

Months									
Years	III	IV	V	VI	VII	VIII	IX	X	Mean/Sum
Temperature (°C)									
2014	5.9	9.7	13.7	15.1	20.5	17.8	13.7	8.4	13.1
2015	4.8	8.2	12.3	16.5	18.7	21.0	14.5	6.5	12.8
2016	2.6	7.4	12.4	17.2	19.4	17.7	13.2	9.6	12.4
Rainfalls (mm)									
2014	36.3	39.5	79.5	74.2	37.5	105.7	26.3	3.0	402.0
2015	53.1	30.0	100.2	43.3	62.6	11.9	77.1	39.0	417.2
2016	33.8	44.3	23.0	101.6	48.7	52.6	109.8	14.4	428.2

Table 2. Sielanianov's hydrothermal index K (mm/°C).

Years	Months								Mean
	III	IV	V	VI	VII	VIII	IX	X	
2014	1.98	1.50	2.30	1.20	0.16	1.90	0.62	0.12	1.22
2015	3.57	1.22	1.02	0.87	1.08	0.18	1.77	1.93	1.45
2016	4.19	1.99	0.60	1.97	0.81	0.96	2.77	0.48	1.72

K: <0.5—drought; 0.5–1.0—semi-drought; 1.0–1.5—optimal moisture; >1.5—excessive moisture [39].

In the years of research, average temperatures in the growing seasons coincided with the average values of multiannual temperatures in individual months. The months with the highest average temperatures were July (19.5 °C average) and August (average 18.8 °C). The lowest temperatures in the growing seasons were recorded in April (average 8.4 °C). An analysis of the sums of atmospheric precipitation showed that they were not significantly different in particular vegetation periods. The lowest amount of rainfall was recorded in 2014 (mean 402 mm), and the highest was in 2016 (average 428.2 mm). The average values of precipitation in the years of the experiment were lower than the average multiannual rainfall (mean 415.8 mm).

2.4. Statistical Analysis

The results were statistically analyzed using the analysis of variance for a two-factor experiment, available in the ANOVA program. The least significant differences (LSD) were determined using Tukey's test at a significance level of $p \leq 0.05$. Linear regression equations and correlation coefficients between selected parameters were determined using the Statistica 13.1 software package (StatSoft Inc., Tulsa, OK, USA) for calculations.

3. Results and Discussion

3.1. Soil Physico-Chemical Properties before Establishing the Experiment

The research was conducted on acidic soil with the granulometric composition of sandy loam (Table 3). Total macronutrient content was characteristic of this type of soil [33]. The soil with acidic reactions (pH KCl 5.52–5.68) was characterized by moderate amounts of available forms of phosphorus, potassium and magnesium.

Table 3. Basic soil characteristics.

Specification	Years		
	2014	2015	2016
Fraction 2–0.05 mm (%) Sand	64	66	64
Fraction 0.05–0.002 mm (%) Silt/Salt	27	27	27
Fraction < 0.002 mm (%) Clay	9	8	9
pH	5.52	5.64	5.68
C _{tot} g·kg ^{−1}	11.49	10.53	13.68
N _{tot} g·kg ^{−1}	1.29	1.08	1.32
P _{tot} g·kg ^{−1}	0.42	0.58	0.63
K _{tot} g·kg ^{−1}	0.83	0.63	0.56
Mg _{tot} g·kg ^{−1}	0.50	0.41	0.43
S _{tot} g·kg ^{−1}	0.14	0.12	0.14
Available forms:			
P·mg·kg ^{−1}	55	67	78
K·mg·kg ^{−1}	123	168	132
Mg·mg·kg ^{−1}	74	61	62

3.2. The Fresh Matter Yield of Maize Grown for Silage

During the field experiment, an effect of differentiated mineral fertilizer combinations and a long-term effect of the organomineral fertilizer based on lignite waste on the production of silage maize were investigated. The fresh matter yield of maize grown for silage (Table 4) recorded in the experiment significantly varied in subsequent years, depending on fertilizer treatment varieties in the first year of research and on the interaction of the experimental factors.

Table 4. The fresh matter yield of maize grown for silage (Mg·ha^{−1}).

Fertilization	Cultivars			Research Years			Average
	Silien	P8000	PR38A79	2014	2015	2016	
Control	52.0 D,a	59.5 C,a	59.5 D,a	33.5 C,b	68.3 C,a	69.2 B,a	57.0 C
NPKMgS	79.0 C,b	93.9 B,a	89.8 C,a	61.3 B,b	101.5 B,a	99.9 A,a	87.6 B
NPKMgS + N1	102.5 A,a	104.4 A,a	97.2 B,a	72.4 A,b	115.3 A,a	116.2 A,a	101.3 A
NPKMgS + N2	91.8 B,b	103.7 A,a	104.9 A,a	70.2 A,b	118.3 A,a	111.9 A,a	100.1 A
NPKMgS + N3	95.2 B,a	97.7 B,a	97.7 B,a	72.3 A,b	109.0 B,a	109.3 A,a	96.9 A
Average	84.1 C	91.8 A	89.8 B	61.9 B	102.5 A	101.3 A	

Means marked with the same letters in each column and means in rows marked with large font letters do not differ significantly.

The highest average yields of fresh matter were obtained on the plots with NPKMgS + N1 in 2014 (72.4 Mg·ha^{−1}) and in 2016 (116.2 Mg·ha^{−1}) and with NPKMgS + N2 in 2015 (118.3 Mg·ha^{−1}). To those plots, 1 Mg·ha^{−1} and 5 Mg·ha^{−1} of organomineral fertilizer based on lignite waste were applied to the preceding crop, respectively. The above yields were 2.2, 1.7 and 1.7 times higher, respectively, than the yield of control plants. Of the varieties, the medium late type in 2014 and the medium early type in 2015 and 2016 yielded the best results. This may indicate their high yield potential, also reported by other authors [40,41], mainly related to their longer growing season. Some studies [29,42]

indicated a high impact of soil evaporation and plant transpiration on the maize yield, and Li et al. [43] recorded the highest yields when access to water and nitrogen was optimal. In the present experiment the highest yield was noted in 2015 ($102.5 \text{ Mg}\cdot\text{ha}^{-1}$). As indicated by the results presented in Diagram 1, the highest yield of fresh matter ($101.3 \text{ Mg}\cdot\text{ha}^{-1}$) was on the plot with NPKMgS + N1, on which $1 \text{ Mg}\cdot\text{ha}^{-1}$ of the organomineral fertilizer and $60 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ were applied to the preceding crop.

3.3. Nitrogen, Phosphorus, Potassium, Magnesium and Sulphur Content in Maize Biomass

The chemical composition of silage maize is the result of treatment, soil and weather conditions and growing methods and varieties [44]. In the present experiment maize average total nitrogen content was significantly differentiated by fertilizer treatment, varieties and the years of research (Table 5). Treatment combinations resulted in a significant reduction in maize nitrogen content compared to control. According to Skowrońska and Filipek [14] an increase in the maize yield decreased nitrogen concentration in plants. In the present research, according to statistical analysis, the highest average nitrogen concentration ($14 \text{ g}\cdot\text{kg}^{-1} \text{ DM}$) across treatment combinations and years was in maize from the plot with NPKMgS + N2 and in control plants. The medium late variety (PR 38A79) accumulated the largest amounts of nitrogen. A significant effect of varieties on the level of nitrogen and protein in maize biomass was confirmed by other research [45]. In the present studies the largest amounts of nitrogen were recorded as a response to all treatment combinations in 2015. Of all nutrients, nitrogen increases crop yields to the greatest extent [46], which was also confirmed by the present research.

Table 5. The nitrogen, phosphorus, potassium, magnesium and sulphur content in maize biomass ($\text{g}\cdot\text{kg}^{-1}\text{DM}$).

	Treatments	N	P	K	Mg	S
Fertilization	Control	14.0 ± 1.19^a	2.58 ± 0.54^a	11.16 ± 1.03^a	0.97 ± 0.09^a	0.50 ± 0.06^a
	NPKMgS	11.3 ± 1.08^b	1.98 ± 0.21^c	9.48 ± 0.96^a	0.85 ± 0.09^a	0.47 ± 0.06^a
	NPKMgS + N1	12.8 ± 1.03^a	2.04 ± 0.20^b	9.34 ± 0.89^a	0.79 ± 0.09^a	0.48 ± 0.05^a
	NPKMgS + N2	14.0 ± 1.09^a	1.94 ± 0.18^d	9.55 ± 0.85^a	0.86 ± 0.10^a	0.51 ± 0.04^a
	NPKMgS + N3	12.7 ± 1.02^a	1.84 ± 0.17^e	8.93 ± 0.84^b	0.80 ± 0.08^a	0.48 ± 0.04^a
	P	*	*	*	n.s.	n.s.
Cultivars	Silen	12.5 ± 1.01^a	1.94 ± 0.17^b	9.89 ± 0.79^b	0.82 ± 0.07^b	0.48 ± 0.03^a
	P8000	12.9 ± 0.99^a	2.15 ± 0.19^a	9.62 ± 0.76^a	0.86 ± 0.08^a	0.48 ± 0.02^a
	PR38A79	13.4 ± 1.05^a	2.13 ± 0.17^a	9.55 ± 0.81^a	0.88 ± 0.09^a	0.50 ± 0.02^a
	P	*	*	*	*	n.s.
Research years	2014	13.5 ± 1.07^a	2.07 ± 0.18^a	10.04 ± 0.85^a	1.06 ± 0.09^a	0.45 ± 0.02^b
	2015	15.0 ± 1.21^a	2.21 ± 0.16^a	9.67 ± 0.81^a	0.75 ± 0.08^b	0.51 ± 0.03^a
	2016	10.3 ± 0.98^b	1.95 ± 0.15^b	9.37 ± 0.80^a	0.75 ± 0.08^b	0.51 ± 0.02^a
	P	*	*	n.s.	*	*

The level of significance are indicated by an asterisk (* $p \leq 0.05$); n.s.—not significant; mean $\pm$ SD; the values designated by different lower case letters are significantly different (results of Tukey test).

The bioavailability of phosphorus largely depends on soil pH [47], plant species and fertilizer treatment [48]. The concentration of phosphates in the soil solution is very low, and low temperatures after plant emergence additionally inhibit the uptake of phosphorus [49,50]. In a statistically significant way, its largest amounts were found in silage maize harvested from control, and fertilizer treatment resulted in a significant reduction in phosphorus content (Table 5). That was a result of the dilution of this chemical element in higher yields of maize, which was confirmed by other research [14]. The lowest phosphorus content was recorded in plants treated with NPKMgS + N3, with a high yield of maize harvested from that plot (Table 4). The content of this chemical element remained similar across varieties but it varied across years. The highest was for plants harvested in 2015 ($2.21 \text{ g}\cdot\text{kg}^{-1}\text{DM}$), and the lowest in 2016 ($1.95 \text{ g}\cdot\text{kg}^{-1}\text{DM}$).

The linear regression equation and the correlation coefficient (YFM = $209.9971 - 58.4861\text{P}$ $r = -0.9223$) indicate a significant negative relationship between phosphorus content in maize dry matter and its yield (Figure 2a). At the same time, the linear regression

equation and the correlation coefficient ($Kp = 3.7344 + 2.8697Pp$ $r = 0.9766$) indicate a significant positive relationship between phosphorus and potassium content in maize DM (Figure 2b).

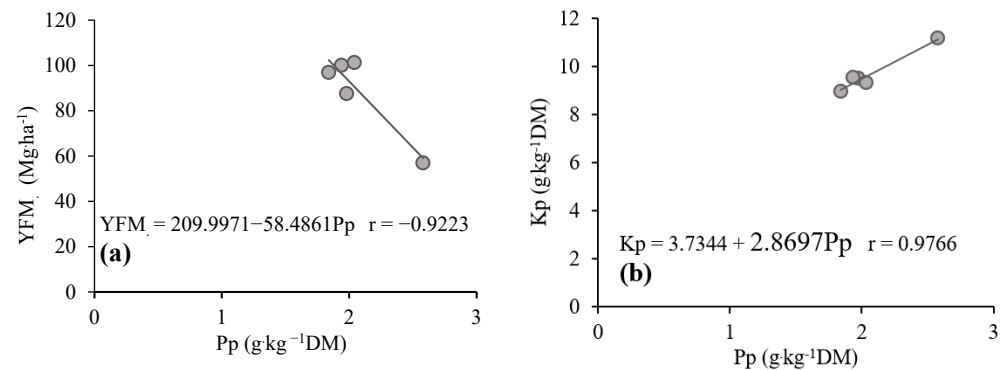


Figure 2. (a) The correlations between phosphorus content in maize dry matter (Pp) and its yield (YFM), (b) phosphorus (Pp) and potassium (Kp) content in maize dry matter.

The highest potassium content ($11.16 \text{ g} \cdot \text{kg}^{-1} \text{DM}$) was found in control plants, while the lowest ($8.93 \text{ g} \cdot \text{kg}^{-1} \text{DM}$) in plants treated with NPKMgS + N3 (Table 5). Like in the case of phosphorus, that was caused by the dilution of this chemical element in a large yield. In their study, Bruns and Ebelhar [51] pointed to the relationship between an increase in soil potassium content and the concentration of this element in maize. Obtaining high yields of fodder plants is associated with reducing the content of ingredients in the yield of biomass as a result of dilution of ingredients in high yields. The concept of “component dilution” has been introduced [14,43]. Across varieties, the highest potassium content was found in the early Silien one ($9.89 \text{ g} \cdot \text{kg}^{-1} \text{DM}$) in 2014. It was significantly higher (by 15.75%) than the content of the medium late PR 38A79 variety. Across subsequent years of research, no significant differences in potassium content were noted. According to other publications, potassium content of silage maize is at an optimal level [30] for forage plants [51].

Mineral treatment combinations significantly reduced magnesium content in maize (Table 5). The lowest was in plants collected from plots treated with NPKMgS+ N1, with high yields harvested there. The magnesium content of maize dry matter was negatively significantly correlated with potassium content and the fresh matter yield (Figure 3).

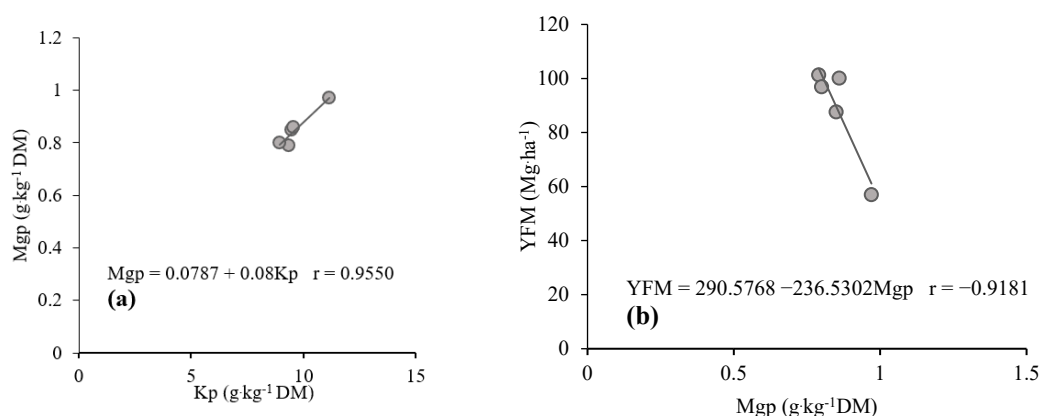


Figure 3. (a) The correlations between magnesium (Mgp) and potassium (Kp) content in maize dry matter (Pp), (b) magnesium (Mgp) and fresh matter yield (YFM).

The highest phosphorus content was in 2014 ($1.06 \text{ g} \cdot \text{kg}^{-1} \text{DM}$), with significantly lower amounts in 2015 and 2016 ($0.75 \text{ g} \cdot \text{kg}^{-1} \text{DM}$).

Sulphur deficiency may be one of the main causes of a decrease in the quantity and quality of crops [52,53]. The applied mineral treatment and varieties did not have a significant impact on maize sulphur content, which ranged from 0.45 to 0.51 g·kg⁻¹DM (Table 5). In 2015 and 2016, there was a significant (by 13.3%) increase in sulphur content compared to the first year of research (2014). The main contributor to the lower content of sulphur in maize harvested in 2014 could have been unfavorable meteorological conditions during the vegetation period. This relationship was confirmed by other authors [54,55].

3.4. Uptake of Nitrogen, Phosphorus, Potassium, Magnesium and Sulphur

The amounts of nitrogen, phosphorus, potassium, magnesium and sulphur in maize biomass result from their concentration and the yield (Table 6). According to statistical analysis, treatment combinations, varieties and years of research affected those amounts in a statistically significant way. The highest statistically significant nitrogen uptake in relation to control was recorded in plants treated with NPKMgS + N2 applied in subsequent years of research. On those plots, 5 Mg·ha⁻¹ of the organomineral fertilizer based on lignite waste, pre-sowing and 60 kg·N·ha⁻¹ as a top dressing were applied to the preceding crop. According to Skowrońska [10], for typical grain maize varieties, the amount of nitrogen taken up by plants reached 450 kg·N·ha⁻¹, and the negative gross nitrogen balance was -180 kg·N·ha⁻¹ (i.e., it was nitrogen taken up from the soil).

Table 6. Nitrogen, phosphorus, potassium, magnesium and sulphur uptake with the yield of maize grown for silage (kg·ha⁻¹).

Treatments		N	P	K	Mg	S
Fertilization	Control	277.6 ± 20.1 ^c	51.6 ± 3.6 ^c	221.8 ± 29.1 ^c	17.3 ± 2.1 ^c	10.5 ± 1.4 ^c
	NPKMgS	351.1 ± 27.5 ^b	61.9 ± 4.2 ^b	293.4 ± 27.4 ^b	25.6 ± 2.6 ^b	14.5 ± 1.1 ^b
	NPKMgS + N1	471.7 ± 25.6 ^a	74.2 ± 5.3 ^a	340.2 ± 29.3 ^a	27.8 ± 2.4 ^a	17.2 ± 1.8 ^a
	NPKMgS + N2	514.3 ± 35.8 ^a	73.6 ± 4.7 ^a	353.2 ± 31.7 ^a	30.9 ± 3.2 ^a	18.3 ± 1.6 ^a
	NPKMgS + N3	467.9 ± 31.7 ^a	67.7 ± 4.5 ^a	328.5 ± 30.8 ^a	28.6 ± 3.8 ^a	17.5 ± 1.3 ^a
P		*	*	*	*	*
Cultivars	Silien	395.4 ± 37.4 ^b	62.1 ± 4.9 ^b	306.1 ± 12.3 ^a	24.5 ± 1.8 ^b	15.7 ± 1.1 ^a
	P8000	426.7 ± 36.2 ^a	68.7 ± 4.8 ^a	306.5 ± 11.9 ^a	26.3 ± 1.8 ^a	15.6 ± 1.2 ^a
	PR38A79	427.6 ± 37.1 ^a	66.6 ± 4.3 ^a	306.7 ± 12.1 ^a	27.3 ± 1.9 ^a	15.6 ± 1.2 ^a
	P	*	*	n.s.	*	n.s.
Research years	2014	279.1 ± 24.5 ^c	41.4 ± 6.9 ^c	201.9 ± 32.6 ^c	21.1 ± 2.3 ^b	8.3 ± 2.1 ^b
	2015	593.3 ± 37.5 ^a	86.9 ± 9.5 ^a	383.6 ± 31.8 ^a	29.8 ± 1.9 ^a	20.1 ± 2.4 ^a
	2016	377.2 ± 33.9 ^b	69.2 ± 7.6 ^b	336.8 ± 30.7 ^b	27.1 ± 2.1 ^a	18.3 ± 2.9 ^a
	P	*	*	*	*	*

The level of significance are indicated by an asterisk (* $p \leq 0.05$); n.s.—not significant; mean ± SD; the values designated by different lower case letters are significantly different (results of Tukey test).

The uptake of phosphorus by maize grown for silage was significantly affected by the experimental factors. Thus, the highest uptake of phosphorus (74.2 kg·ha⁻¹) was recorded for plants treated with NPKMgS + N1. Across varieties it was the highest for the medium early P8000 type and for the medium late PR38A79 type. In 2015, plants took up the largest amounts of phosphorus. Similar amounts of phosphorus taken up by maize (65 kg·P·ha⁻¹) were presented in other studies.

Statistical analysis showed a significant impact of treatment and years on the potassium uptake. Thus, the highest potassium uptake by maize (353.2 kg·ha⁻¹) was recorded on plots with NPKMgS + N2. Large differences in the potassium uptake in subsequent years of research were due to weather conditions (Tables 1 and 2). Statistical analysis showed a significant impact of treatment, varieties and years of research on the magnesium uptake by maize grown for silage (Table 6). Its highest value across years of research (30.9 kg·ha⁻¹) was recorded in plants treated with NPKMgS + N2. On those plots, 5 Mg·ha⁻¹ of the organomineral fertilizer based on lignite waste pre-sowing and a top dressing of 60 kg·N·ha⁻¹ were applied. Maize grown for silage in 2015 took up significantly larger amounts of magnesium (29.8 kg·ha⁻¹) than in 2014.

Statistical analysis showed a significant effect of treatment and years of research on the sulphur uptake by maize grown for silage. Thus, the highest average sulphur uptake

(18.3 kg·ha⁻¹) was recorded for plants treated with NPKMgS + N2. In 2015, maize took up significantly larger amounts of sulphur (20.1 kg·ha⁻¹) than in 2014. A significantly lower uptake of sulphur in 2014 was mainly a result of low yields.

3.5. Agronomic and Physiological Efficiency of Nitrogen, Phosphorus, Potassium, Magnesium and Sulphur Treatment

The values of agronomic efficiency (AE) of nitrogen in mineral fertilizers (polyfoska® M-MAKS NPKMgS and urea) are presented in Table 7. The highest (133 kg·kg⁻¹N) was recorded for maize treated with NPKMgS + N1. On this plot, 1 Mg·ha⁻¹ of the organomineral fertilizer based on lignite waste was applied pre-sowing to the preceding crop (maize). Some studies [56] reported a decrease in AE to 76 kg·kg⁻¹N after the application of YaraRega, a compound fertilizer, applied to the soil surface and by fertigation. Studies carried out in South Africa [57] have confirmed a reduction in agronomic efficiency in response to increasing doses of mineral nitrogen. In the present experiment, the highest AE of nitrogen among varieties was recorded for early and medium early ones (Silien and P800). Across experimental years, its highest value was noted in 2015 (129 kg·kg⁻¹N).

Table 7. Agronomic efficiency of nitrogen, phosphorus, potassium, magnesium and sulphur treatment (kg·kg⁻¹).

	Treatments ^a	N	P	K	Mg	S
Fertilization	NPKMgS	106 ± 21 ^b	302 ± 47 ^b	84 ± 19 ^b	882 ± 159 ^c	756 ± 136 ^c
	NPKMgS + N1	133 ± 25 ^a	452 ± 62 ^a	128 ± 21 ^a	1333 ± 185 ^b	1143 ± 141 ^a
	NPKMgS + N2	119 ± 20 ^a	476 ± 65 ^a	133 ± 24 ^a	1386 ± 179 ^a	1188 ± 138 ^a
	NPKMgS + N3	98 ± 19 ^b	449 ± 61 ^a	125 ± 25 ^a	1310 ± 181 ^b	1123 ± 146 ^b
	<i>P</i>	*	*	*	*	*
Cultivars	Silien	118 ± 18 ^a	437 ± 60 ^a	122 ± 23 ^a	1272 ± 163 ^a	1091 ± 129 ^a
	P8000	120 ± 18 ^a	432 ± 61 ^a	122 ± 23 ^a	1271 ± 161 ^a	1091 ± 124 ^a
	PR38A79	105 ± 15 ^b	391 ± 54 ^b	110 ± 21 ^b	1140 ± 157 ^b	977 ± 128 ^b
	<i>P</i>	*	*	*	*	*
Research years	2014	112 ± 14 ^a	409 ± 51 ^b	116 ± 19 ^b	1205 ± 138 ^b	1033 ± 127 ^b
	2015	129 ± 17 ^a	477 ± 63 ^a	133 ± 25 ^a	1391 ± 145 ^a	1193 ± 125 ^a
	2016	101 ± 13 ^b	373 ± 52 ^c	104 ± 18 ^c	1087 ± 149 ^c	931 ± 121 ^c
	<i>P</i>	*	*	*	*	*

The level of significance are indicated by an asterisk (* $p \leq 0.05$); n.s.—not significant; mean ± SD; the values designated by different lower case letters are significantly different (results of Tukey test).

The AE of phosphorus in polyfoska® M-MAKS NPKMgS is presented in Table 7. Statistical analysis indicated a significant impact of phosphorus treatment, varieties and years of research on its AE. The high AE of phosphorus resulted not only from its dosage but also from nitrogen, potassium, magnesium and sulphur treatment, as well as from the treatment applied to the preceding crop. The highest AE of phosphorus (476 kg·kg⁻¹P) was noted for maize treated with NPKMgS + N2. On this plot, 5 Mg·ha⁻¹ of the organo-mineral fertilizer based on lignite waste was applied pre-sowing to the preceding crop, which was maize. In a statistically significant way, the lowest AE of phosphorus was for the PR 38A79 variety. For maize grown in 2015, the highest AE of phosphorus (477 kg·kg⁻¹P) was recorded.

Statistical analysis indicated a significant impact of treatment, varieties and years of research and the interaction of the factors on the AE of potassium. The highest average AE of this chemical element (133 kg·kg⁻¹K) was noted for maize treated with NPKMgS + N2. On that plot, 5 Mg·ha⁻¹ of the organomineral fertilizer based on lignite waste (100-35-125 kg·NPK ha⁻¹) pre-sowing, and 60 kg·N·ha⁻¹ as a top dressing were applied to the preceding crop. In the second year of research (2015), the highest AE of potassium (133 kg·kg⁻¹K) was observed.

The AE of magnesium in M-MAKS NPKMgS polyfoska® is presented in Table 7. Its highest value (1386 kg·kg⁻¹Mg) was obtained for maize treated with NPKMgS + N2. It was similar for the Silien and P8000 varieties (1272 and 1271 kg·kg⁻¹Mg, respectively). In

the second year, the highest AE of magnesium ($1391 \text{ kg} \cdot \text{kg}^{-1} \text{Mg}$) was recorded. Nitrogen treatment applied pre-sowing increased the AE of magnesium.

The treatment of maize with polyfoska[®], M-MAKS NPKMgS and urea ($100\text{-}35\text{-}125\text{-}12\text{-}14 \text{ kg} \cdot \text{ha}^{-1} + 40 \text{ kg} \cdot \text{N} \cdot \text{ha}^{-1}$ as a top dressing) made it possible to achieve the highest value of sulphur agronomic efficiency ($1188 \text{ kg} \cdot \text{kg}^{-1} \text{S}$). Across varieties, the highest statistically significant AE of sulphur was for Silien and P8000. In the second year of research (2015), the highest AE of sulphur treatment was recorded ($1193 \text{ kg} \cdot \text{kg}^{-1} \text{S}$).

The physiological efficiency (PE) of macronutrients in mineral fertilizers (polyfoska[®], M-MAKS NPKMgS and urea) taken up by maize grown for silage is presented in Table 8. For nitrogen, its statistically significant highest value ($153 \text{ kg} \cdot \text{kg}^{-1} \text{N}$) was recorded in maize treated with polyfoska[®], M-MAKS and NPKMgS ($100\text{-}35\text{-}125\text{-}12\text{-}14 \text{ kg} \cdot \text{ha}^{-1}$). Doses of mineral nitrogen (N1, N2 and N3) applied in a top dressing significantly reduced the PE of nitrogen. The decrease in PE was the result of a significantly higher nitrogen uptake with the yield of maize fertilized with NPKMgS + N1, NPKMgS + N2 and NPKMgS in relation to the control. For varieties, the highest statistically significant value was noted for the early Silien variety ($105 \text{ kg} \cdot \text{kg}^{-1} \text{N}$) with $100 \text{ kg} \cdot \text{kg}^{-1} \text{N}$ for the medium early P8000 variety. Studies on spring wheat [52] indicated that PE of nitrogen and sulphur was higher than their AE obtained under the influence of nitrogen treatment. For silage maize grown in 2016, the highest PE was observed ($107 \text{ kg} \cdot \text{kg}^{-1} \text{N}$).

Table 8. Physiological efficiency of nitrogen, phosphorus, potassium, magnesium and sulphur treatment ($\text{kg} \cdot \text{kg}^{-1}$).

	Treatments ^a	N	P	K	Mg	S
Fertilization	NPKMgS	153 ± 28^a	1144 ± 180^a	151 ± 27^a	1296 ± 193^b	3137 ± 254^a
	NPKMgS + N1	91 ± 22^b	714 ± 153^b	137 ± 23^b	1545 ± 224^a	2501 ± 183^b
	NPKMgS + N2	71 ± 20^b	880 ± 141^b	134 ± 21^b	1301 ± 153^b	2274 ± 168^c
	NPKMgS + N3	86 ± 24^b	1128 ± 162^a	155 ± 24^a	1521 ± 184^a	2580 ± 197^b
	<i>p</i>	*	*	*	*	*
Cultivars	Silien	105 ± 15^a	925 ± 133^b	146 ± 26^a	1546 ± 175^a	2665 ± 257^b
	P8000	100 ± 13^a	967 ± 141^a	147 ± 26^a	1448 ± 149^b	2837 ± 234^a
	PR38A79	96 ± 11^b	1008 ± 141^a	140 ± 21^b	1253 ± 193^c	2368 ± 188^c
	<i>p</i>	*	*	*	*	*
Research years	2014	100 ± 12^a	929 ± 123^c	141 ± 25^a	1485 ± 153^a	2558 ± 251^c
	2015	93 ± 10^b	961 ± 137^b	132 ± 23^b	1476 ± 147^a	2605 ± 184^b
	2016	107 ± 16^a	1009 ± 134^a	158 ± 26^a	1286 ± 138^b	2707 ± 228^a
	<i>p</i>	*	*	*	*	*

The level of significance are indicated by an asterisk (* $p \leq 0.05$); n.s.—not significant; mean $\pm$ SD; the values designated by different lower case letters are significantly different (results of Tukey's post hoc test).

The main cause of the reduction in the PE of phosphorus was a higher uptake of that mineral by maize on plots where a nitrogen top dressing was used in doses of 20 and $40 \text{ kg} \cdot \text{N} \cdot \text{ha}^{-1}$. This relationship confirms the stimulating effect of balanced nitrogen treatment on the phosphorus uptake during plant vegetation [58]. The high PE of phosphorus resulted not only from its dose but also from nitrogen, potassium, magnesium and sulphur treatment, as well as from treatment applied to the preceding crop. The highest PE phosphorus ($1144 \text{ kg} \cdot \text{kg}^{-1} \text{P}$) was obtained for maize treated with NPKMgS. On that plot, $100\text{-}35\text{-}125 \text{ kg} \cdot \text{NPK} \cdot \text{ha}^{-1}$ (mineral fertilizers, manure at a dose of $30 \text{ Mg} \cdot \text{ha}^{-1}$) and a top dressing of $60 \text{ kg} \cdot \text{N} \cdot \text{ha}^{-1}$ were applied to the preceding crop. For subsequent years of research, significantly increasing the values of PE of phosphorus ($929 < 961 < 1009 \text{ kg} \cdot \text{kg}^{-1} \text{P}$) were noted.

The highest PE of potassium ($155 \text{ kg} \cdot \text{kg}^{-1} \text{K}$) was obtained for maize treated with NPKMgS + N3. On that plot, $100\text{-}35\text{-}125 \text{ kg} \cdot \text{NPK} \cdot \text{ha}^{-1}$ (mineral fertilizers, manure at a dose of $30 \text{ Mg} \cdot \text{ha}^{-1}$) and a top dressing of $60 \text{ kg} \cdot \text{N} \cdot \text{ha}^{-1}$ were applied. In the third year (2016) the highest potassium PE was recorded ($158 \text{ kg} \cdot \text{kg}^{-1} \text{K}$).

The highest PE of magnesium ($1545 \text{ kg} \cdot \text{kg}^{-1} \text{Mg}$) was obtained for maize treated with NPKMgS + N1. On this plot, $1 \text{ Mg} \cdot \text{ha}^{-1}$ of organomineral fertilizer based on lignite waste ($100\text{-}35\text{-}125 \text{ kg} \cdot \text{NPK} \cdot \text{ha}^{-1}$) was applied pre-sowing to the preceding crop, i.e., maize, with

60 kg·N·ha⁻¹ as a top dressing. Nitrogen treatment applied as a top dressing increased the agronomic efficiency of magnesium. Its highest value was for the early Silien variety (1546 kg·kg⁻¹Mg). In the first year of research (2014), the highest PE of magnesium treatment was recorded (1485 kg·kg⁻¹Mg).

Nitrogen treatment (N1, N2 and N3) applied as a top dressing significantly reduced the PE of sulphur in the first and second years of research and insignificantly in the third year of research (Table 8). The treatment of maize with NPKMgS (100-35-125-12-14 kg·ha⁻¹) resulted in the highest value of the PE of sulphur (3137 kg·kg⁻¹S). Among the varieties, it was the highest for P8000, a medium early one (2837 kg·kg⁻¹S). In the third year, the highest PE of sulphur was noted (2707 kg·kg⁻¹S).

The AE of nitrogen was significantly negatively correlated with the PE of phosphorus (Table 9). Significant relationships occurred between the AE of phosphorus and the AE of potassium, magnesium and sulphur and between the PE of nitrogen and sulphur. The AE of potassium was correlated with the AE of magnesium and sulphur and with the PE of nitrogen and sulphur. Significant relationships were also noted between the AE of magnesium and the PE of nitrogen and sulphur. The PE of nitrogen was significantly positively correlated with the PE of sulphur (Table 8). From the agronomic point of view, positive correlations between the agronomic efficiency of N, P, K, Mg and S and the physiological efficiency of N, P, K, Mg and S are the most favorable. Under natural field conditions, this is impossible to achieve because of the biochemical processes in plants.

Table 9. Correlation coefficients for the relationship between AE (N, P, K, Mg and S) and PE (N, P, K, Mg and S).

Efficiency	AEN	AEP	AEK	AEMg	AES	PEN	PEP	PEK	PEMg	PES
AEN	-									
AEP	0.37	-								
AEK	0.41	0.99 *	-							
AEMg	0.40	0.99 *	0.99 *	-						
AES	-0.40	0.99 *	0.99 *	0.99 *	-					
PEN	-0.31	0.99 *	-0.98 *	-0.99 *	-0.99 *	-				
PEP	-0.97 *	-0.59	-0.62	-0.61	-0.61	0.53	-			
PEK	-0.87	-0.52	-0.54	-0.53	-0.53	0.51	0.88	-		
PEMg	0.18	0.46	0.47	0.48	0.48	-0.38	-0.31	0.13	-	
PES	-0.44	-0.98 *	-0.97 *	-0.97 *	-0.97 *	0.98 *	0.64	0.66	-0.28	-

* Significant for $p \leq 0.05$.

4. Conclusions

The highest average yields of maize grown for silage (118.3 Mg·ha⁻¹) were recorded on the plots with NPKMgS + N1 and NPKMgS + N2. On the basis of the three-year studies using polyfoska® M-MAKS (NPKMgS), potassium salt and urea in the cultivation of maize for silage, the optimal dose of mineral fertilizers NPKMgS + N1 (pre-sowing 100-35-125-12-14 kg·ha⁻¹ and a top dressing of 20 kg·N·ha⁻¹) and NPKMgS + N2 (pre-sowing 100-35-125-12-14 kg·ha⁻¹ and a top dressing of 40 kg·N·ha⁻¹) can be recommended. The organomineral fertilizer based on lignite waste in doses of 1 Mg·ha⁻¹ and 5 Mg·ha⁻¹ applied to the preceding crop on NPKMgS + N1 and NPKMgS + N2 plots positively affected maize parameters (uptake, AE and PE).

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