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Yield and Quality of Maize Grain in Response to Soil Fertilization with Silicon, Calcium, Magnesium, and Manganese and the Foliar Application of Silicon and Calcium: Preliminary Results

Arkadiusz Artyszak [1,*], Dariusz Gozdowski [1], Jerzy Jonczak [1], Krzysztof Pągowski [1], Rafał Popielec [1] and Zahoor Ahmad [2]

1 Institute of Agriculture, Warsaw University of Life Sciences—SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland; dariusz_gozdowski@sggw.edu.pl (D.G.); jerzy_jonczak@sggw.edu.pl (J.J.); krzysztof_pagowski@sggw.edu.pl (K.P.)

2 Department of Botany, Constituent College of University of Central Punjab, Bahawalpur Campus Airport Road Bahawalpur, Bahawalpur 63100, Pakistan

* Correspondence: arkadiusz_artyszak@sggw.edu.pl; Tel.: +48-22-5932702

Abstract: Climate change is forcing the search for innovative solutions to effectively reduce its harmful effects on food production. In addition, increasingly stringent regulations are being introduced in the European Union (the European Green Deal), mandating reductions in mineral fertilizer doses, which can reduce crop yields. One innovative technology could be soil fertilization and foliar application of Si-based fertilizers. A two-year field experiment (2023 and 2024), in commercial crop conditions in Kraski (52°2′42″ N, 18°54′6″ E), in Central Poland, studied the effect of differentiated soil fertilization and the foliar application of Si-based products on the yield and quality of maize grain at two levels of nitrogen/phosphorus/potassium (NPK) fertilization (100% and 50%). The soil fertilizer SiGS® (Si—200 g kg^{-1}, Ca—181 g kg^{-1}, Mg—46 g kg^{-1}, and Mn—45 g kg^{-1}) was applied to the soil at doses of 100, 300, and 500 kg ha^{-1}, alone or with Barrier Si-Ca® (Si—336 g dm^{-3}; Ca—207 g dm^{-3}) foliar fertilizer (1 dm^3 ha^{-1}). The number of combinations assessed is 16. The effects were compared against the control treatment. The experiment evaluated plant physiological parameters, grain and dry matter yield, grain moisture content and quality (protein, fat, and starch content), and grain yield components. The highest grain yields were obtained with soil fertilization at a dose of 500 kg ha^{-1} (giving an increase of 17.5%), at a dose of 300 kg ha^{-1} plus foliar application (+16.4%), and at a dose of 500 kg ha^{-1} plus foliar application (+17.8%). The increase in grain yield in treatments with a half-rate of NPK was of a similar magnitude (on average, +11.9%) to the full rate (+12.6%) compared to the control treatments. Doubling the NPK rate contributed to an increase in grain yield of 7.8%. The applied fertilization had a significant and beneficial effect on the protein and fat content of the grain, while it reduced the starch content.

Keywords: silicon; maize; foliar application; drought; NPK

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1. Introduction

Maize (*Zea mays* L.) is one of the most important crops in the world. In 2023, the area of maize cultivated for grain amounted to 208.2 million ha, yielding 5.96 t ha^{-1}, with 1211.6 million t being harvested. In the EU, the area under maize was 8.3 million ha, yielding 7.35 t ha^{-1} and harvesting 60.1 million t [1].

Maize carries out a C4 photosynthetic cycle in which it assimilates carbon dioxide (CO_2) in two successive, spatially separated stages. In this way, it eliminates photorespiration, which has a beneficial effect on the photosynthetic efficiency of the plant [2].

Maize yield is limited by the impact of several stresses caused by abiotic and biotic factors, the former primarily being drought. Therefore, innovative ways to limit yield reduction are being sought. In terms of nutrients, nitrogen (N) has the greatest impact on maize yield [3], but the European Union (EU) has restrictive regulations on N fertilization. In Poland, the maximum amount of N from all sources (soil; natural, organic, mineral soil; and foliar fertilizers) allowed in maize cultivation for grain has been set at 240 kg N ha^{-1} [4]. The European Green Deal assumes that, by 2030, the EU will have reduced nutrient losses by 50%, which means reducing the dose of mineral fertilizers by 20% [5]. Reducing fertilizer use can reduce yields and therefore reduce the profitability of agricultural production. Therefore, innovative methods are being sought to achieve this goal.

One of these methods may be the use of plant-growth-promoting rhizobacteria. The results of studies using growth activators and bacterial preparations containing plant-growth-promoting rhizobacteria have indicated that it is possible to reduce N fertilization by 30–40% while maintaining the same maize grain yields or even more [6]. The yield and quality of maize grain can be improved by the combined foliar application of N, boron (B), and zinc (Zn) [7].

The effects of reduced NPK fertilization can also be reduced by fertilizing with silicon, which reduces the impact of abiotic and biotic factors that cause stress to plants. In recent years, there has been increasing interest in beneficial elements—-primarily silicon (Si), as evidenced by the rapidly growing number of publications on Si since 2000 [8]. The role of Si has been emphasized as a beneficial factor in increasing the resistance and productivity of crops [9]. Restoring natural cycles of reactive Si allows for improving sustainable development by reducing the use of phosphorus (P) fertilizers and increasing the resistance of crops to pest feeding [10]. Silicon supplementation can mitigate the negative effects of potassium (K) deficiency and improve maize yields on soils with low K content [11]. The addition of Si contributes to greater nutrient uptake by maize plants. On clayey soil, the use of potassium silicate (K_2O_3Si) can increase the availability of P, K, Ca, Mg, S, Cu, and Si, and on sandy soil, it can increase the availability of N, P, K, Mg, Si, and Cu [12]. Silicon alleviates drought-induced yield reduction in maize [10], especially in the late vegetative and early reproductive stages [13]. The soil application of Si improves maize plant growth by improving its physiological and biochemical attributes under drought stress and the presence of cadmium (Cd) [14]. The foliar application of SiNP can also mitigate Cd toxicity [15]. Silicon application has been associated with increases in the content of anthocyanins, ascorbic acid, total phenols, and flavonoids, thus mitigating the effects of salinization in maize cultivation [16]. Silicon also has a place in mitigating climate change through the long-term sequestration of carbon (C) in phytoliths [17].

Due to the diverse responses of different crops to Si, it is necessary to conduct specific studies and develop application methodologies adapted to each plant species. By precisely determining the dosage, application method, and timing of Si application, its potential benefits can be significantly increased [18].

There is relatively little information on soil fertilization with Si in maize cultivation under European conditions, one of the reasons being the applicable legislation. There are significantly more publications on the effects of the foliar application of products containing different forms of Si.

Under controlled conditions, the foliar application of sodium silicate (Na_2O_3Si) with iron (Fe) was found to have a positive effect on the relative chlorophyll content, selected chlorophyll fluorescence parameters, and gas exchange in maize plants grown under different soil salinity conditions. However, these results have not yet been verified under field conditions, in which various environmental factors can modify the responses of plants to stress conditions and foliar Si application [19]. For this reason, field experiments performed under maize production conditions are particularly important, having great practical value.

The aim of this study was to evaluate the influence of different variants of soil fertilization with a fertilizer containing Si, Ca, Mg, and Mn and foliar application of a fertilizer containing Si and Ca on the yield and quality of maize grain in central Poland. The following research hypotheses were put forward:

1. Soil application of a fertilizer containing Si, Ca, Mg, and Mn and foliar application of a fertilizer containing Si and Ca have a beneficial effect on grain and dry matter yields of maize.
2. Grain and dry matter yields of maize are higher when higher doses of Si-based soil fertilizer are applied.
3. The most favorable combination for the highest grain and dry matter yields is soil fertilization with Si, Ca, Mg, and Mg plus foliar application of Si and Ca.

2. Materials and Methods

2.1. Soil Conditions

In the years 2023 and 2024, a field experiment was conducted, using maize as the grain, under commercial crop conditions in Kraski (52°2′42″ N, 18°54′6″ E), in Central Poland (Figure 1).

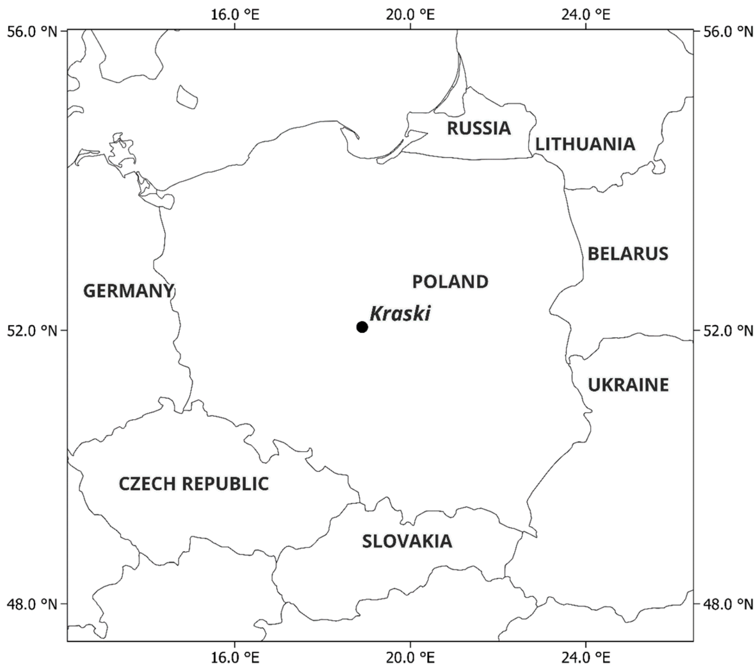

Figure 1. Location of the field experiments.

The experiment was conducted on Cambisols [20]. In order to further characterize soil conditions, soil samples were taken from the 0–30 and 30–60 cm layers. The soil had a loamy sand or sandy loam texture in the 0–30 cm layer and contained 74.4–82.7% sand (0.05–2.0 mm), 13.0–17.8% silt (0.002–0.05 mm), and 3.8–11.2% clay (<0.002 mm). In the 30–60 cm layer, the soils contained 51.6–82.3%, 10.0–20.5%, and 6.5–32.9% of these textural fractions, representing the sandy loam or silt–clay loam textural groups. Based on the results of a particle-size analysis, the soils were classified as light or medium in the 0–30 cm layer and medium, rarely light or heavy, in the 30–60 cm layer.

Soil samples were collected from two soil depths (0–30 and 30–60 cm) in spring before fertilization. The soil samples were analyzed in the Department of Soil Science at WULS–SGGW in Warsaw. The contents of the mineral forms of N (nitrate [NO_3-N] and ammonium [NH_4-N]) were determined in fresh samples, just after sampling and homogenization. Approximately 5 g of sample were placed into polytetrafluoroethylene extraction tubes at two replicates, and 50 mL of 1% potassium sulfate (K_2SO_4, pure per analysis grade, Fluka, Germany) solution was added. The samples were left for 24 h and then filtered through quantitative paper filters. The content of NO_3-N in extracts was determined colorimetrically (spectrophotometer 6105 UV-VIS, Jenway, London, UK) using sodium salicylate (pure per analysis grade, Avantor, Gliwice, Poland), and the NH_4-N was determined using Nessler reagent (prepared based on pure per analysis reagents, Avantor, Poland). Additionally, the content of water was determined in the fresh soil samples by the gravimetric method. The water content was taken into account when calculating the NO_3-N and NH_4-N contents.

The remaining soil samples were dried at room temperature and then sieved through a 2.0 mm sieve to remove the gravel fraction. All analyses were performed on the earth fraction (<2.0 mm). Part of each sample was additionally ground into powder for chemical analysis.

The soil pH was determined potentiometrically (SevenDirect SD23, Stäfa, Switzerland) in a suspension with 1 mol dm^{-3} potassium chloride (KCl, pure per analysis grade, Avantor, Poland) solution in a soil-to-KCl ratio of 1:2.5.

The total carbon (TC) and N contents were determined by dry combustion (Vario MacroCube, Elementar, Langenselbold, Germany). The inorganic carbon (IC) was determined by Scheibler's volumetric procedure. The total organic carbon was calculated as TC–IC. The analysis included two replicates.

The contents of the bioavailable forms of macronutrients (P, K, and Mg) and micronutrients (B, Cu, Fe, Mn, and Zn) were determined by inductively coupled plasma atomic emission spectrometry (Avio 200, Perkin Elmer, Shelton, CT, USA) prior to sample extraction using the Mehlich III procedure [21]. The extraction solution was prepared based on ACS or pure per analysis grade reagents (Avantar, Gliwice, Poland; Supelco, Darmstadt, Germany; Thermo Scientific, Bratislava, Slovakia).

The bioavailable forms of Si were determined by inductively coupled plasma atomic emission spectrometry (Avio 200, Perkin Elmer, Shelton, CT, USA) prior to soil sample extraction in a 0.01 mol dm^{-3} calcium chloride ($CaCl_2$, pure per analysis grade, Sigma Aldrich, Hamburg, Germany) solution. Approximately 1.5 g of air-dried soil was placed into a 50 mL Falcon tube to which 25 mL of $CaCl_2$ solution was added. The samples were shaken for 16 h, centrifuged at 3000 rpm for 5 min, and filtered through hard paper filters. The Si content was determined in the extracts.

The characteristics of the soil conditions in the spring before applying the fertilizers are presented in Table 1. The pH value, organic carbon, mineral nitrogen, and bioavailable macro- and micronutrient content were similar in both years of the study. The exception was the bioavailable silicon content, which was lower in 2024 than in 2023. The 0–30 cm soil layer mostly had a higher pH value, a higher organic carbon and mineral N content, and more available nutrients than the 30–60 cm layer.

Table 1. Soil conditions before establishing the experiment with maize (means of all the treatments, 2023 and 2024).

Soil Layer, cm	pH_{KCl}	Soil Organic Carbon %	mg kg^{-1}		Nmin, kg ha^{-1}	The Bioavailable Forms, mg kg^{-1}			
			$N-NO_3$	$N-NH_4$		P	K	Mg	Si
2023/100% NPK [1]									
0–30	6.3	0.79	5.45	2.59	34.7	222	173	84.1	70.4
30–60	5.4	0.37	3.47	2.88	27.0	111	116	119	76.1
2023/50% NPK									
0–30	6.5	0.77	5.18	2.55	34.1	254	189	72.1	51.6
30–60	5.0	0.28	3.28	2.80	25.4	95.8	131	121	59.8
2024/100% NPK									
0–30	6.3	0.75	4.38	5.89	46.2	251	225	82,5	34.2
30–60	5.1	0.28	2.62	2.93	25.0	77	107	91.6	41.1
2024/50% NPK									
0–30	6.2	0.70	4.88	5.43	46.2	252	255	76.4	38.1
30–60	4.8	0.30	3.25	2.54	24.5	88	138	79.3	37.1

Soil Layer, cm	The Bioavailable Forms, mg kg^{-1}				
	B	Cu	Fe	Mn	Zn
2023/100% NPK [1]					
0–30	0.66	2.09	217	80.0	7.21
30–60	0.50	1.60	123	41.6	2.05
2023/50% NPK					
0–30	0.58	1.78	266	72.1	7.17
30–60	0.43	1.32	125	47.5	1.95
2024/100% NPK					
0–30	0.23	3.75	288	78.0	7.85
30–60	0.08	3.57	129	64.9	3.19
2024/50% NPK					
0–30	0.32	3.78	284	67.1	6.98
30–60	0.06	3.33	132	68.0	2.50

[1] 100% NPK—N—212 kg ha^{-1}, P—36.6 kg ha^{-1}, K—68.9 kg ha^{-1}, Mg—30.2 kg ha^{-1}, and S—52.8 kg ha^{-1}; 50% NPK—N—106 kg ha^{-1}, P—18.3 kg ha^{-1}, K—34.5 kg ha^{-1}, Mg—15.1 kg ha^{-1}, and S—26.4 kg ha^{-1}.

2.2. Weather Conditions

The vegetation period (May–September) in 2024 was more favorable for maize vegetation than in 2023 due to the greater total rainfall and its distribution (Table 2). July and August were characterized by particularly high average monthly temperatures. Analysis of the hydrothermal coefficient values shows that in 2023 May was quite dry, June was optimum, July was dry, August was optimum, and September was very dry. In 2024, May was very dry, June was quite humid, July was optimum, and August, and September were quite humid [22].

Table 2. Weather conditions during the maize growing season (2023–2024).

Month	Precipitation, mm	Average Monthly Temperature, °C	Hydrothermal Coefficient [1]
2023			
May	42.5	13.3	1.03
June	72.7	18.3	1.32
July	59.1	20.1	0.95
August	93.8	20.8	1.45
September	24.2	18.0	0.45
Sum	292.3	–	–

Table 2. *Cont.*

Month	Precipitation, mm	Average Monthly Temperature, °C	Hydrothermal Coefficient [1]
		2024	
May	22.6	16.8	0.43
June	108.8	19.0	1.91
July	101.3	20.9	1.56
August	112.5	20.5	1.77
September	83.5	16.7	1.67
Sum	428.7		–

[1] Hydrothermal coefficient = Σ x/Σ t × 10, where Σ x and Σ t are accordingly the sum of precipitations and temperatures in the period when the temperature has not been lower than 10 °C. This coefficient is a measure of rainfall efficiency. Source: own study based on date [23] (for station Zduny).

2.3. Production Technology

The grain maize was grown in monoculture in the third and fourth years after grain maize. After harvesting the forecrop, disk harrowing was performed to a depth of approximately 12 cm. Pre-sowing fertilization was carried out using urea with a urease inhibitor (N = 460 g kg^{-1}) at a dose of 400 and 200 kg ha^{-1}, respectively, ESTA Kieserit Gran® (S = 200 g kg^{-1}, Mg = 151 g kg^{-1}) at 200 and 100 kg ha^{-1}, and with SiGS® fertilizer. The fertilizers were mixed to a depth of approximately 30 cm using a no-tillage unit. On 1 May 2023 and 30 April 2024, the maize was sown using a Gaspardo precision seeder with simultaneous intercrop fertilization. For the fertilization, Polifoska 8® fertilizer (N = 80 g kg^{-1}, P = 105 g kg^{-1}, K = 197 g kg^{-1}, S = 36 g kg^{-1}) was used at doses of 350 and 175 kg ha^{-1}. The total mineral fertilization amounted (per hectare) to (for 100% NPK) N = 212 kg, P = 36.6 kg, K = 68.9 kg, Mg = 30.2 kg, and S = 52.8 kg; for 50% NPK, N = 106 kg, P = 18.3 kg, K = 34.5 kg, Mg = 15.1 kg, and S = 26.4 kg.

For both years of the study, seeds of the DKC 3888® maize variety were used [24]. This is a medium-late (FAO number: 270) hybrid variety with a very high and stable level of grain yield. It is characterized by very good initial vigor and produces medium-high plants with strong stems, well-developed root systems, very good health, and a high tolerance to lodging. It produces flex-type cobs and dent-type grain. It tolerates periodic water shortages in the soil and high temperatures well. The sowing rate in the study was 82,000 seeds ha^{-1}, the inter-row spacing was 75 cm, and the sowing depth was 5 cm. The seed material was dressed with Redigo M 120 FS® dressing (metalaxyl = 20 g dm^{-3} + prothioconazole = 100 g dm^{-3}). To control weeds, the herbicide Lumax 537.5 SE® (active substance: mesotrione = 37.5 g dm^{-3} + s-metolachlor = 312.5 g dm^{-3} + terbuthylazine = 187.5 g dm^{-3}) at a dose of 3.5 dm^3 in 240 dm^3 of water ha^{-1} was used The treatment was applied on 4 May 2023 and 2 May 2024. No chemical treatments were applied against diseases or pests.

2.4. Experimental Methodology

This was a two-factor experiment, established in a randomized complete block design, with four replicates for each treatment. The individual plot area was 625 m^2. The total number of plots was 64. The total area of the experiment was 4.0 ha.

The first factor (A) was the NPK doses—100% using farm technology (without the intervention of the research team) and 50%—and the second (B) was the method of fertilizing using Si, both on the soil and as a foliar application.

The experiment used SiGS® soil fertilizer (Eramet, Øyesletta, Norway) and Barrier Si-Ca® foliar fertilizer (Cosmocel, San Nicolás de los Garza, Mexico). Currently, SiGS® fertilizer is not available on the EU market (Tables 3 and 4). SiGS is a pure slag from the electric smelting process for the production of SiMn metal. It has been approved in Norway for agricultural use, making the SiGS® fertilizer 98–99% amorphous. In 2024, the producer started the process of registering the fertilizer in Poland as the first of the EU countries.

Foliar application of the Barrier Si-Ca® fertilizer was carried out based on the experiment schedule on 10 June 2023 and 7 June 2024. The dose of the working liquid was 300 dm^3 ha^{-1}.

Table 3. Chemical compositions of products used in the experiment.

Product	Content
SiGS®	Si—200 g kg^{-1}, Ca—181 g kg^{-1}, Mg—46 g kg^{-1}, Mn—45 g kg^{-1}
Barrier Si-Ca®	Si—336 g dm^{-3}, Ca—207 g dm^{-3}

Source: information provided by producers.

Table 4. Treatments applied in the experiment.

Treatment No. and Abbreviation	Dose of SiGS®, kg ha^{-1}	Barrier Si-Ca®, dm^3 ha^{-1}	Total Dose of Elements, kg ha^{-1}
	100% NPK [1] (A1)		
1 (A1B1)	–	–	–
2 (A1B2)	100	–	Si—20, Ca—18.1, Mg—4.6, Mn—4.5
3 (A1B3)	300	–	Si—60, Ca—54.3, Mg—13.8, Mn—13.5
4 (A1B4)	500	–	Si—100, Ca—90.5, Mg—23, Mn—22.5
5 (A1B5)	–	1	Si—0.34, Ca—0.21
6 (A1B6)	100	1	Si—20.3, Ca—18.3, Mg—4.6, Mn—4.5
7 (A1B7)	300	1	Si—60.3, Ca—54.5, Mg—13.8, Mn—13.5
8 (A1B8)	500	1	Si—100.3, Ca—90.7, Mg—23, Mn—22.5
	50% NPK [2] (A2)		
9 (A2B1)	–	–	–
10 (A2B2)	100	–	Si—20, Ca—18.1, Mg—4.6, Mn—4.5
11 (A2B3)	300	–	Si—60, Ca—54.3, Mg—13.8, Mn—13.5
12 (A2B4)	500	–	Si—100, Ca—90.5, Mg—23, Mn—22.5
13 (A2B5)	–	1	Si—0.34, Ca—0.21
14 (A2B6)	100	1	Si—20.3, Ca—18.3, Mg—4.6, Mn—4.5
15 (A2B7)	300	1	Si—60.3, Ca—54.5, Mg—13.8, Mn—13.5
16 (A2B8)	500	1	Si—100.3, Ca—90.7, Mg—23, Mn—22.5

[1] 100% NPK—N—212 kg ha^{-1}, P—36.6 kg ha^{-1}, K—68.9 kg ha^{-1}, Mg—30.2 kg ha^{-1}, and S—52.8 kg ha^{-1}; [2] 50% NPK—N—106 kg ha^{-1}, P—18.3 kg ha^{-1}, K—34.5 kg ha^{-1}, Mg—15.1 kg ha^{-1}, and S—26.4 kg ha^{-1}.

2.5. Measurements in the Experiment

Several plant physiological parameters were measured three times during the growing season: in the 6th leaf stage—BBCH 16 (2 June 2023, 3 June 2024); in the 9th leaf stage—BBCH 19 (16–17 June 2023, 17 June 2024); and in the full flowering stage—BBCH 65 (10–11 July 2023, 10 July 2024) [25]. BBCH is a decimal scale used to determine the stages of growth and development of individual plant species. The abbreviation BBCH is derived from the German Biologische Bundesanstalt, Bundessortenamt, und CHemische Industrie.

They included the leaf area index (LAI), photosynthetically active radiation (PAR) absorption, Normalized Difference Vegetation Index (NDVI), and SPAD-measured chlorophyll content. The LAI is the ratio of leaf area to surface area, which provides an indication of the extent to which plants use light. PAR absorption indicates the absorption by plants of the radiation used in photosynthesis (wavelengths from 400 nm to 700 nm). NDVI is an indicator that allows plant health to be assessed. NDVI is based on the contrast between the highest reflection in the near-infrared band and absorption in the red band. Higher values of the index correspond to higher reflectance in the infrared range and lower reflectance in the red range. A high value of the index corresponds to good coverage of the field by vegetation. The measurement of the chlorophyll content of SPAD involves measuring the differences in light absorption by the leaf at 650 and 940 nm. The 650 nm wavelength is close to the maximum absorption of light by chlorophyll a (680 nm) and chlorophyll b (660 nm), while 940 nm is near-infrared radiation, whose absorption by the leaf is very low. The result is given in units called SPAD units (Soil–Plant Analysis Development), which report the relative concentration of chlorophyll in the leaf, and this is closely correlated with nitrogen content. The LAI and PAR were measured above the canopy (II) and below the canopy (Iu) using an AccuPar® probe (Meter, Pullman, WA, USA). The NDVI was measured using a GreenSeeker® device (Trimble, Westminster, CO, USA). The chlorophyll content in the maize leaves was measured using a Minolta SPAD 502Plus® chlorophyll meter (Konica Minolta Sensing Europe B.V., Nieuwegen, The Netherlands) on the highest leaf, in its middle part. The physiological traits were measured in 10 plants in four representative locations on each treatment, the measurements taken from the same plants each time.

The fresh weight yield was assessed in the second half of September 2023 and 2024. For this purpose, 4 samples were taken from each combination with an area of 1 m^2 each. Representative plant samples of 100 g were then taken from each sample, which were sliced and dried at a temperature not exceeding 60 °C with forced air circulation according to Polish Standard PN-R-04013 [1988] [26] in the laboratory of the Department of Agronomy of the Warsaw University of Life Sciences. The dry matter yield was determined on the basis of the dry matter content.

Cob samples were collected in the first half of October 2023 and 2024. Four samples of 1 m^2 (133 cm of a randomly selected representative row) were selected for harvesting from each treatment. The plants were counted. The cobs were picked by hand, counted, and the cover leaves were removed. The number of cobs per plant was calculated as the quotient of the number of cobs and the number of plants. The kernels were counted in five randomly selected cobs from each sample.

The cobs were transported to the laboratory in the Department of Agronomy at the Institute of Agriculture at the Warsaw University of Life Sciences, where the kernels (grain) were removed and weighed. The grain quality was then assessed (moisture, fat, protein, and starch contents) using an Infratec 1241 Grain Analyzer® (FOSS, Hilleroed, Denmark). The mass of 1000 grains at their current moisture content was determined in accordance with the Polish Standard PN-EN ISO 520 [2010] [27]. A densimeter with a capacity of 0.25 dm^3 was used to determine the grain density.

The results obtained were converted into the grain yield per hectare at a standard moisture content of 14%. A similar procedure was followed to determine the mass of 1000 grains. The following formula was used for the calculations: $P = Po \times (100 - Zw)/86$, where P = grain yield at 14% moisture content (in kilograms), Po = grain yield at the moisture content during harvest (in percent), and Zw = grain moisture content during harvest (in percent).

The grain yield per cob was calculated as the quotient of the grain yield and the number of cobs. In accordance with the requirements of the project this study was a part of, the grain yield and its moisture content in 2023 were published so they could be distributed to agricultural advisors and farmers [28].

2.6. Statistical Analysis

The results obtained from the experiment were subjected to statistical analysis, including an analysis of variance (ANOVA) and multiple comparisons using the Tukey procedure. The ANOVA was performed for each year separately and as a combined analysis for two years together, where factors were years of the study (Y), dose of NPK (A), and fertilization treatment (B). In the ANOVA model all interactions between the factors were included. A significance level of $p = 0.05$ was set for the comparison of means. Based on this, homogeneous groups of means were distinguished, which were marked with subsequent letters. Standard errors calculated for each treatment/factor level were presented as parameters of variability. An assessment of the relationships between the studied features was made based on the values of simple Pearson correlation coefficients. The significance of the correlations was assessed at $p \leq 0.05$ and $p \leq 0.01$. Principal component analysis (PCA) was performed to evaluate multivariate relationships between grain yield and physiological parameters. The analyses were carried out using Statistica 13® software (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

The interaction of the study years with the NPK dose had a significant effect on most of the assessed physiological parameters, except for the NDVI value and SPAD chlorophyll content on the first and second measurement dates and the PAR absorption value on the second measurement date (Table 5). The interaction of the study year with the fertilization treatment significantly affected all physiological parameters, except for the LAI value and the SPAD chlorophyll content on the first measurement date. The interaction of the NPK dose with the fertilization treatment significantly affected all the assessed parameters on the first measurement date, the LAI value and PAR absorption on the second date, and the NDVI value and SPAD chlorophyll content on the third date.

The interaction between the study year, NPK dose, and fertilization treatment had a significant effect on all the assessed physiological parameters, except for the NDVI value on the first measurement date and the LAI value on the third date.

The study year had a significant effect on all assessed physiological parameters on each measurement date. The NPK dose significantly affected the LAI value for all measurement dates, the PAR absorption value on the first measurement date, and the NDVI value and chlorophyll content on the third measurement date. The fertilization treatment significantly affected all assessed parameters on each measurement date, except for the SPAD chlorophyll content on the first measurement date and the NDVI value on the second measurement date.

Table 5. The *p*-values based on analysis of variance of the assessed physiological parameters in the years 2023 and 2024.

Term of Measurement	Physiological Parameter	Years of the Study (Y)	Dose of NPK (A)	Fertlization Treatment (B)	Y × A	Y × B	A × B	Y × A × B
I [1]	LAI	<0.05	<0.05	<0.05	<0.05	0.436	<0.05	<0.05
	PAR absorption	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	NDVI	<0.05	0.891	<0.05	0.717	<0.05	<0.05	0.102
	SPAD	<0.05	0.734	0.072	0.245	0.080	<0.05	<0.05

Table 5. *Cont.*

Term of Measurement	Physiological Parameter	Years of the Study (Y)	Dose of NPK (A)	Fertlization Treatment (B)	Y × A	Y × B	A × B	Y × A × B
II	LAI	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	PAR absorption	<0.05	0.123	<0.05	0.067	<0.05	<0.05	<0.05
	NDVI	<0.05	0.754	0.058	0.657	<0.05	0.236	<0.05
	SPAD	<0.05	0.520	<0.05	0.785	<0.05	0.151	<0.05
III	LAI	<0.05	<0.05	<0.05	<0.05	<0.05	0.055	0.079
	PAR absorption	<0.05	0.711	<0.05	<0.05	<0.05	0.590	<0.05
	NDVI	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	SPAD	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

[1] term I—BBCH 16; term II—BBCH 19; term III—BBCH 65.

The NDVI value in 2023 on the first measurement date was the highest for treatment A2B2, on the second date for treatments A1B6 and A2B5, and on the third date for treatment A1B1 (Figure S1). On average, for both NPK doses, the values of the NDVI on the first date for treatments B2 and B3 were significantly higher, and for treatment B4 were significantly lower than for treatment B1. On the second date, the values were similar for all treatments in relation to treatment B1, and on the third date, all treatments, except for treatment B4, were characterized by a significantly lower NDVI value than for treatment B1. The NDVI value in 2023 was significantly different depending on NPK fertilization on the second and third measurement dates and was higher when higher doses of fertilizer were used. The NDVI values in 2024 on the first measurement date were the highest for treatments A1B2 and A2B3; on the second date for treatments A1B8 and A2B3; and on the third date for treatment A1B6 (Figure S2). On average, for both NPK doses, the value of the NDVI on the first date for treatment B3 was significantly higher, and for treatments B4 and B7 significantly lower, than for treatment B1. On the second date, the values were similar for all treatments in relation to treatment B1, except for treatment B4, in which it was significantly lower, and on the third date, all treatments had similar NDVI values to treatment B1. The NDVI value in 2024 was significantly different depending on NPK fertilization only on the first measurement date, and was higher when higher doses of fertilizer were used. In 2023–2024, the value of the NDVI in the first measurement term was the highest for treatments A1B2, A1B3, A2B2, and A2B3; in the second term for treatment A1B3; and in the third term for treatments A1B1, A1B4, and A1B6 (Figure S3). On average, for both NPK doses, the values of the NDVI in the first term for treatments B2 and B3 were significantly higher and, in treatments B4 and B7, significantly lower than in treatment B1. In the second term, the values were similar for all treatments in relation to treatment B1, with the exception of treatment B7, in which it was significantly lower, and in the third term, treatments B2, B3, B5, B7, and B8 were characterized by significantly lower NDVI values than treatment B1. On average, for both years of the study, the NDVI values were significantly different depending on NPK fertilization on the first and third measurement dates and were higher when using higher doses of fertilizer (Figure S3).

The LAI value in 2023 on the first measurement date was the highest for treatment A2B3, on the second date for treatment A2B2, and on the third date for treatment A1B2 (Figure S4). On average, for both NPK doses, the values of the LAI on the first date for treatment B3 were significantly higher than for treatment B1; on the second date, they were similar for all treatments in relation to treatment B1, with the exception of treatments B4, B7, and B8, which gave significantly lower values. On the third date, treatments B2 and B3 were characterized by significantly higher LAI values than for treatment B1, while treatments

B5, B6, and B8 had significantly lower LAI values than treatment B1. The LAI values in 2023 were significantly different depending on NPK fertilization on the third measurement date and were higher when using higher doses of fertilizer. The LAI values in 2024 on the first measurement date were the highest for treatments A1B1 and A1B8, on the second measurement date for treatments A1B4 and A1B7, and on the third measurement date for treatment A2B3 (Figure S5). On average, for both NPK doses, the values of the LAI on the first measurement date for treatments B2, B5, and B6 were significantly lower than for treatment B1 and were similar for the remaining treatments. On the second measurement date, for all treatments except for treatments B2 and B8, the values were significantly higher, being similar on the third measurement date, except for treatment B5, which was similar to treatment B1. The LAI values in 2024 were significantly different depending on NPK fertilization on the first and second measurement dates and were higher when using higher doses of fertilizer.

In the years 2023 and 2024, the LAI on the first measurement date was the highest for treatment A1B8, on the second date for treatment A1B5, and on the third date for treatment A2B3 (Figure S6). On average, for both NPK doses, the index values on the first date for treatments B2 and B5 were significantly lower than for treatment B1, while the remaining treatments were similar to treatment B1. On the second date, the values were similar for all treatments in relation to treatment B1, except for treatments B3, B4, B5, and B7, which had significantly higher values, and on the third date, all treatments, except for treatments B5 and B7, had significantly higher LAI values than treatment B1. On average, for both years of the study, the LAI values were significantly different depending on NPK fertilization on the first measurement date and were higher when higher doses of fertilizer were used.

The PAR absorption values in 2023, on the first measurement date, were the highest for treatment A2B3, on the second date for treatments A1B3 and A2B2, and on the third date for treatment A1B2 (Figure S7). On average, for both NPK doses, the values of the PAR absorption in the first term for treatment B3 were significantly higher than for treatment B1; in the second term they were similar for all treatments in relation to treatment B1, except for treatments B4, B6, and B7, which had significantly lower values. In the third term, treatments B2 and B3 had significantly higher values than treatment B1, while treatments B5–B8 had significantly lower PAR absorption values than treatment B1. The PAR absorption values in 2023 were significantly different depending on NPK fertilization in the third measurement term and were higher when higher doses of fertilizer were used. The PAR absorption values in 2024 in the first measurement term were the highest for treatments A1B8 and A2B7, in the second term for treatment A2B6, and in the third term for treatment A2B4 (Figure S8). On average, for both NPK doses, the values of the PAR absorption in the first term for treatment B2 were significantly lower than for treatment B1, with the remaining treatments having similar values to treatment B1. In the second term, treatments B2 and B8 had similar values to treatment B1, while in the remaining term the values were significantly higher in relation to treatment B1. In the third term, treatments B3, B4, B6, and B8 had significantly higher PAR absorption values than treatment B1, the remaining treatments having similar values. The PAR absorption values in 2024 did not depend significantly on NPK fertilization.

In the years 2023 and 2024, the PAR absorption values in the first measurement term were the highest for treatment A1B3, in the second term for treatments A1B3, A2B3, and A2B6, and in the third term for treatment A1B3 (Figure S9). On average, for both NPK doses, the values of PAR absorption in the first and second terms for treatment B3 were significantly higher than for treatment B1, with the remaining values being similar. In the third term, treatments B2–B4 were characterized by significantly higher PAR absorption values than treatment B1, with treatment B5 having significantly lower values and treatments B6–B8 having similar values to treatment B1. On average, for both study years, the PAR absorption values were significantly different depending on NPK fertilization in the third measurement term and were higher when higher doses of fertilizer were used.

The SPAD chlorophyll content in 2023 in the first measurement term was the highest for treatment A1B1, in the second term for treatment A2B5, and in the third term for treatments A2B1 and A2B5 (Figure S10). On average, for both NPK doses, the values of the SPAD chlorophyll content in the first term for treatments B2, B4, B5, and B6 were significantly lower than for treatment B1, with the remaining treatments having similar values to treatment B1. In the second term, the values were similar for all treatments in relation to treatment B1, except for treatment B2, which had significantly lower values. In the third term, treatments B2, B4, B7, and B8 had significantly lower SPAD chlorophyll contents than treatment B1, while the remaining treatments had similar values to treatment B1. The SPAD chlorophyll contents in 2023 did not differ significantly depending on NPK fertilization.

The SPAD chlorophyll contents in 2024 in the first measurement term were the highest for treatment A1B6, in the second term for treatment A2B2, and in the third term for treatment A2B6 (Figure S11). On average, for both NPK doses, the values of the SPAD chlorophyll content in the first term for treatment B6 were significantly higher than for treatment B1, with the remaining treatments having similar values to treatment B1. In the second term the values were significantly higher for all treatments in relation to treatment B1, with the exception of treatments B5 and B7, which had similar values. In the third term, treatment B7 had a similar SPAD chlorophyll content to treatment B1, with the remaining treatments having similar values to treatment B1. The SPAD chlorophyll contents in 2024 were significantly different depending on NPK fertilization in the third term and were higher when a lower dose of fertilizer was used.

In the years 2023 and 2024, the SPAD chlorophyll content in the first term of measurement was the highest for treatment A1B6, in the second term for treatment A1B3, and in the third term for treatment A1B6 (Figure S12). On average, for both NPK doses, the values of the SPAD chlorophyll content in the first term for treatment B4 were significantly lower than for treatment B1, whereas the remaining treatments had similar values to treatment B1. In the second term, the values for treatments B3 and B8 were significantly higher than for treatment B1, with the remaining treatments having similar values to treatment B1, and in the third term, all treatments had SPAD chlorophyll contents similar to treatment B1. On average, for both years, the SPAD chlorophyll content was significantly different depending on NPK fertilization in the third measurement term and was higher when lower doses of fertilizer were used.

The study year significantly affected the value of the assessed physiological parameters (Figure S13). In each of the measurement terms, the NDVI, LAI, and PAR absorption values were higher in 2024. The SPAD values in the first measurement term were significantly higher in 2024 but also significantly higher in the second and third measurement terms in 2023.

The variability in the examined physiological parameters decreased in the subsequent measurement terms (Table 6). The lowest SPAD chlorophyll contents were measured in the first and second terms, and the lowest LAI values in the third term.

Table 6. Characterization of statistical variability in the physiological parameters of maize in the years 2023 and 2024.

Term of Measurement	Physiological Parameter	Mean	Min.	Max.	SD	CV, %
I [1]	LAI	0.44	0.08	0.75	0.25	57.76
	PAR absorption	0.54	0.08	1.20	0.36	66.20
	NDVI	31.71	6.40	60.40	18.16	57.26
	SPAD	43.04	29.60	62.60	8.15	18.93
II	LAI	0.69	0.41	0.81	0.08	11.03
	PAR absorption	1.95	0.34	3.80	0.93	47.72
	NDVI	62.84	24.10	93.20	21.36	33.99
	SPAD	42.64	34.00	53.20	3.92	9.20
III	LAI	0.74	0.61	0.81	0.03	4.41
	PAR absorption	4.06	2.08	6.78	1.41	34.78
	NDVI	93.12	81,20	99.20	5.39	5.79
	SPAD	45.86	30.80	56.50	4.20	9.15

[1] term I—BBCH 16; term II—BBCH 19; term III—BBCH 65.

All physiological parameters assessed in Term I had a significant positive relationship with the grain yield and dry-matter yield of the maize (Table 7). In Term II, a significant positive relationship was found for all physiological parameters, except for the SPAD chlorophyll content, which was negative. In Term III, there was a significant positive relationship between the PAR absorption and the grain and dry-matter yields and between the NDVI and grain and dry-matter yields. A significant but negative relationship was found for the SPAD chlorophyll content with grain and dry-matter yield.

For evaluation of multivariate relationships, principal component analysis was performed (Figure 2). The PCA biplot shows that PC1 (33.05%) and PC2 (17.38%) together explain 50.43% of the variance. Variables like NDVI, LAI, and PAR cluster together, indicating strong correlations, while SPAD indices show more spread. Grain yield is moderately correlated with NDVI III. Longer vectors mean stronger contributions, and opposite directions indicate negative correlations. Closer points indicate similar treatments, while distant ones show variation. For example, treatments like A1B6 and A1B8 differ significantly, while A2B1 and A2B5 are more similar.

Table 7. Simple correlation coefficients between physiological parameters and grain and dry-matter yield of maize in the years 2023 and 2024 (n = 96).

Term of Measurement	Physiological Parameter	Grain Yield (at 14% H_2O), t ha^{-1}	Yield of Dry Biomass, t ha^{-1}
I [1]	LAI	0.801 **	0.639 **
	PAR absorption	0.825 **	0.649 **
	NDVI	0.815 **	0.652 **
	SPAD	0.755 **	0.618 **
II	LAI	0.695 **	0.517 **
	PAR absorption	0.803 **	0.612 **
	NDVI	0.787 **	0.617 **
	SPAD	−0.552 **	−0.515 **
III	LAI	0.315	0.170
	PAR absorption	0.830 **	0.650 **
	NDVI	0.801 **	0.615 **
	SPAD	−0.537 **	−0.520 **

[1] term I—BBCH 16; term II—BBCH 19; term III—BBCH 65; ** significant relationships at $p \leq 0.01$.

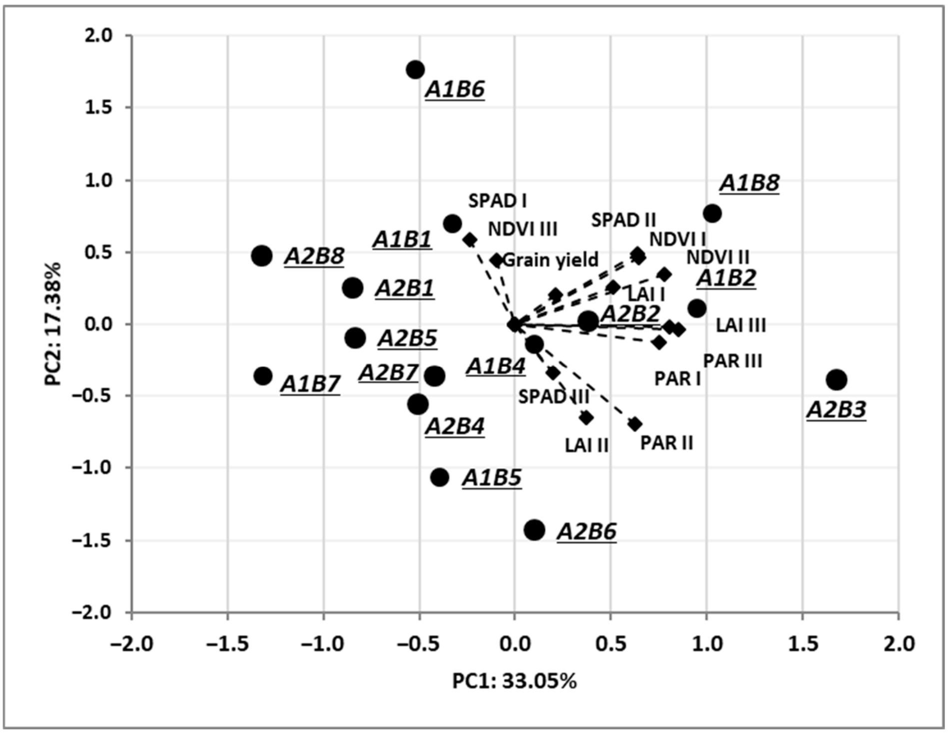

Figure 2. Biplot of PCA presenting multivariate relationships between variables (lines with end of rhombus sjape) and treatments (big dots with underlined labels). I, II, and III are terms of measurement of NDVI, LAI, SPAD, and PAR absorption; A1B1 to A2B8 are abbreviations for the treatments as presented in Table 4. The number of maize plants at harvest was significantly influenced by the study year, interaction of NPK dose and fertilization treatment, and interaction of the study year, NPK dose, and fertilization treatment (Table 8). The highest number of plants at harvest with the full NPK dose was produced by treatments B4 and B6, while the highest number of plants was produced by treatment B4 with the 50% dose.

Table 8. Number of maize plants per hectare at harvest in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in thousands of plants per hectare).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		80.50	ab [1]	85.00	c	82.75	AB
B2		83.50	bc	82.33	abc	82.92	AB
B3		81.83	abc	82.00	abc	81.92	A
B4		84.67	c	85.50	c	85.08	B
B5		78.50	a	82.50	abc	80.50	A
B6		84.67	c	81.83	abc	83.25	AB
B7		83.00	bc	81.50	abc	82.25	AB
B8		84.33	bc	80.50	ab	82.42	AB
Mean		82.63	A	82.65	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.977	0.149	0.585	0.123	<0.05	<0.05

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The grain yield was significantly modified by the study year, NPK dose, fertilization treatment, the interaction of the study year and the fertilization treatment, and the interaction of the study year, the NPK dose, and the fertilization treatment (Table 9). Application of the full NPK dose resulted in a significantly higher grain yield compared to the 50% dose. With the full NPK dose, the highest grain yields were obtained by treatments B3, B4, B7, and B8. With the 50% dose, the highest grain yields were obtained by treatments B4 and B8.

Table 9. Maize grain yield (at 14% moisture content) in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (tonnes per hectare).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		12.47	bc [1]	11.61	a	12.04	A
B2		13.63	de	12.24	ab	12.94	B
B3		14.20	efg	13.15	cd	13.67	C
B4		14.51	fg	13.79	def	14.15	C
B5		13.04	bcd	12.25	ab	12.64	B
B6		13.74	def	12.30	ab	13.02	B
B7		14.52	fg	13.51	de	14.02	C
B8		14.65	g	13.72	def	14.18	C
Mean		13.85	B	12.82	A	–	
p-values based	Y	A	B	Y × A	Y × B	A × B	Y × A × B
on ANOVA	<0.05	<0.05	<0.05	0.445	<0.05	0.883	<0.05

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

Sometimes, maize originally grown for grain is used as green fodder. In that case, the most important feature is the dry-matter yield. The dry-matter yield of the maize depended significantly on the study year, the NPK dose, the fertilization treatment, the interaction of the study years and the fertilization treatment, and the interaction of the NPK dose and the fertilization treatment (Table 10). The full NPK dose resulted in a significantly higher dry-matter yield than the 50% dose. For both doses, the highest dry-matter yield was obtained by treatments B4 and B8 and also by treatment B7 for the 50% dose.

Table 10. Dry-matter yield of maize in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (tonnes per hectare).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		12.7	ab [1]	12.5	a	12.6	A
B2		14.2	cd	13.8	c	14.0	BC
B3		14.9	de	13.4	bc	14.2	BC
B4		15.9	fg	16.2	fg	16.1	DE
B5		14.0	c	13.6	c	13.8	B
B6		15.1	e	14.0	cd	14.6	C
B7		15.4	ef	16.1	fg	15.7	D
B8		16.6	g	16.6	g	16.6	E
Mean		14.9	B	14.5	A	–	
p-values based	Y	A	B	Y × A	Y × B	A × B	Y × A × B
on ANOVA	<0.05	<0.05	<0.05	0.745	<0.05	<0.05	0.364

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The moisture content of the maize grain at harvest was significantly influenced by the study year, fertilization treatment, interaction of study year and fertilization treatment, NPK dose and fertilization treatment, study year, NPK dos,e and fertilization treatment (Table 11). With the full NPK fertilization, the lowest moisture content was achieved by treatments B4, B6, and B7. With the 50% NPK dose, this was achieved by treatment B7.

Table 11. Moisture content of maize grain in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in percent).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		20.22	cdef [1]	19.17	ab	19.69	AB
B2		20.53	defg	21.23	fgh	20.88	C
B3		21.68	h	21.23	fgh	21.46	C
B4		19.47	abc	20.13	bcde	19.80	AB
B5		19.50	abcd	19.42	abc	19.46	AB
B6		19.22	abc	20.92	efgh	20.07	B
B7		19.27	abc	18.88	a	19.08	A
B8		21.77	h	21.30	gh	21.53	C
Mean		20.21	A	20.29	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.670	<0.05	0.771	<0.05	<0.05	<0.05

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The protein content in the grain was significantly influenced by the study year, fertilization treatment, and the interaction of study year and fertilization treatment (Table 12). With the full NPK fertilization, the highest protein content was produced by treatment B8, and with the 50% NPK dose, by treatments B3 and B8.

Table 12. Protein content in maize grain in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in percent).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		8.07	cd [1]	7.90	bc	7.98	B
B2		8.58	ef	8.58	ef	8.58	C
B3		9.40	g	9.12	g	9.26	D
B4		7.73	bc	7.90	bc	7.82	B
B5		8.28	de	8.45	ef	8.37	C
B6		8.42	ef	8.70	f	8.56	C
B7		7.63	ab	7.33	a	7.48	A
B8		9.10	g	9.18	g	9.14	D
Mean		8.40	A	8.40	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.917	<0.05	0.917	<0.05	0.126	0.183

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The fat content in the maize grain was significantly modified by the fertilization treatment (Table 13), with the highest fat content being achieved by treatments B8 and B3 with both full and 50% NPK fertilization.

Table 13. Fat content in maize grain in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in percent).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		4.18	abcd [1]	4.13	abc	4.16	ab
B2		4.18	abcd	4.25	cd	4.22	bc
B3		4.28	cd	4.28	cd	4.28	c
B4		4.08	ab	4.17	abcd	4.13	ab
B5		4.17	abcd	4.15	abcd	4.16	ab
B6		4.17	abcd	4.20	bcd	4.18	abc
B7		4.13	abc	4.03	a	4.08	a
B8		4.28	cd	4.30	d	4.29	c
Mean		4.19	A	4.19	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	0.293	0.880	<0.05	0.230	0.520	0.753	0.851

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The starch content in the maize grain was significantly modified by the study year, fertilization treatment, interaction of study year and fertilization treatment, and the NPK dose and fertilization treatment (Table 14). With the full NPK dose, the highest starch content was achieved by treatments B4 and B7, and with the 50% dose, by treatment B7.

Table 14. Starch content in the maize grain in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in percent).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		72.12	ef [1]	72.22	efg	72.17	C
B2		71.72	cde	71.42	abc	71.57	B
B3		71.07	ab	70.90	a	70.98	A
B4		72.68	gh	71.97	de	72.33	C
B5		72.13	ef	72.15	ef	72.14	C
B6		72.07	ef	71.47	bcd	71.77	B
B7		72.55	fgh	73.02	h	72.78	D
B8		71.03	ab	71.07	ab	71.05	A
Mean		71.92	A	71.78	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.121	<0.05	0.687	<0.05	<0.05	0.528

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The mass of 1000 maize grains was significantly modified by the study year, fertilization treatment, interaction of study years and fertilization treatment, and NPK dose and fertilization treatment (Table 15). With both NPK treatments, the highest mass was observed in grains from treatment B8.

Table 15. Weight of 1000 maize grains (at 14% moisture content) in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in grams).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		324.27	bcd [1]	310.06	ab	317.16	AB
B2		326.26	bcd	349.41	ef	337.83	DE
B3		341.87	def	348.31	ef	345.09	E
B4		327.17	bcd	332.84	cde	330.01	CD
B5		322.52	bc	326.25	bcd	324.39	BC
B6		314.88	bc	331.87	cde	323.37	BC
B7		321.16	bc	294.36	a	307.76	A
B8		352.99	fg	370.78	g	361.89	F
Mean		328.89	A	332.98	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.207	<0.05	0.122	<0.05	<0.05	0.336

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The bulk density of the maize grain significantly depended on the study year, the fertilization treatment, and the interaction of the study year and the NPK dose (Table 16). In both treatments of NPK fertilization, the highest bulk density was noted for treatment B8.

Table 16. Maize grain bulk density in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in kilograms per hl).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		70.61	bc [1]	67.27	ab	68.94	AB
B2		71.30	bcd	76.64	def	73.97	C
B3		75.10	cde	71.45	bcd	73.28	C
B4		69.90	abc	73.22	cde	71.56	BC
B5		72.08	bcd	70.95	bc	71.52	BC
B6		70.90	bc	72.44	bcd	71.67	BC
B7		70.40	bc	64.39	a	67.39	A
B8		78.52	ef	81.15	f	79.83	D
Mean		72.35	A	72.19	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.869	<0.05	<0.05	0.528	0.061	0.131

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

The study year, NPK dose, and fertilization treatment significantly modified the number of kernels per cob (Table 17). With both NPK doses, the highest number of kernels per cob was achieved by treatment B7, with the full NPK dose producing a significantly higher number of kernels per cob compared with the 50% dose.

Table 17. Number of kernels per cob in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization.

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		456.07	abc [1]	439.66	abc	447.86	A
B2		507.51	def	418.35	a	462.93	A
B3		481.57	bcd	448.43	abc	465.00	A
B4		532.85	ef	472.26	bcd	502.56	B
B5		456.53	abc	452.93	abc	454.73	A
B6		486.17	cde	431.94	ab	459.06	A
B7		551.49	f	550.29	f	550.89	C
B8		472.74	bcd	454.02	abc	463.38	A
Mean		493.12	B	458.49	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	<0.05	<0.05	0.106	0.058	0.174	0.101

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at p = 0.05.

Study year, NPK dose, fertilization treatment, and interaction of study year and fertilization treatment significantly influenced the grain yield from a single cob (Table 18). With a full NPK dose, the highest grain yield from a single cob was produced by B7, and with a 50% dose, treatment B8. Application of the full NPK dose resulted in a significantly higher grain yield from a single cob compared with the half dose.

Table 18. Grain yield (at 14% moisture content) from a single corn cob in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization (in grams).

Treatment		Dose of NPK					
		A1		A2		Mean	
B1		144.59	abc [1]	133.23	a	138.91	A
B2		162.25	efgh	145.47	abc	153.86	BC
B3		164.25	fghi	154.02	bcdef	159.13	CD
B4		172.69	hi	155.39	cdefg	164.04	D
B5		146.55	bcd	143.89	abc	145.22	AB
B6		151.10	bcde	141.76	ab	146.43	AB
B7		175.20	i	158.09	defg	166.65	D
B8		165.50	fghi	166.29	ghi	165.89	D
Mean		160.26	B	149.77	A	–	
p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	<0.05	<0.05	0.133	<0.05	0.308	0.313

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at p = 0.05.

Study year; interaction of study year and fertilization treatment; interaction of NPK dose and fertilization treatment; and study year, NPK dose, and fertilization treatments significantly influenced the number of cobs produced per plant (Table 19). With the full NPK dose, treatments B4 and B7 produced a significantly lower number of cobs than the control treatment, while with 50% NPK, all treatments produced similar results.

Table 19. Number of cobs per plant in the years 2023 and 2024 depending on (A) NPK dose and (B) fertilization.

Treatment	Dose of NPK					
	A1		A2		Mean	
B1	1.08	bc [1]	1.03	ab	1.05	AB
B2	1.01	ab	1.03	ab	1.02	A
B3	1.06	ab	1.05	ab	1.05	AB
B4	1.00	a	1.04	ab	1.02	A
B5	1.14	c	1.03	ab	1.09	B
B6	1.06	ab	1.06	ab	1.06	AB
B7	1.00	a	1.05	ab	1.03	A
B8	1.05	ab	1.03	ab	1.04	A
Mean	1.05	A	1.04	A	–	

p-values based on ANOVA	Y	A	B	Y × A	Y × B	A × B	Y × A × B
	<0.05	0.386	0.061	0.130	<0.05	<0.05	<0.05

A1—100% NPK; A2—50% NPK; B1—control; B2—SiGS (100 kg ha^{-1}); B3—SiGS (300 kg ha^{-1}); B4—SiGS (500 kg ha^{-1}); B5—Barrier Si-Ca (1 dm^3 ha^{-1}); B6—SiGS (100 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B7—SiGS (300 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); B8—SiGS (500 kg ha^{-1}) + Barrier Si-Ca (1 dm^3 ha^{-1}); [1] the same lowercase letters mean no significant differences between the treatments of NPK dose size and fertilization treatments, while the same uppercase letters mean no significant differences between the means for fertilization treatments (this applies to the last column) or between the means for NPK dose sizes (comparisons in rows). All mean comparisons are at $p = 0.05$.

Among the assessed maize yield and quality traits, the highest variability was observed in the number of kernels per cob (coefficient of variation, CV = 20.48%), and the lowest in the starch content in the grain (CV = 1.09%) (Table 20).

Table 20. Characterization of statistical variability in grain maize yield characteristics in the years 2023 and 2024.

Trait	Mean	Minimum	Maximum	Standard Deviation (SD)	Coefficient of Variation (CV), %
Number of plants during harvest, thousand plants ha^{-1}	82.64	70.00	90.00	5.05	6.11
Grain yield (14% H_2O), t ha^{-1}	13.33	9.85	17.474	1.81	13.58
Dry matter yield, t ha^{-1}	13.42	10.08	16.68	1.75	13.00
Grain moisture, %	20.25	16.70	26.70	2.09	10.31
Protein content, %	4.19	3.80	4.70	0.14	3.38
Fat content, %	8.40	6.80	9.80	0.74	8.86
Starch content, %	71.85	69.30	73.40	0.79	1.09
Weight of 1000 grains, g	330.94	251.33	400.50	32.97	9.96
Grain bulk density, kg hL^{-1}	72.27	43.90	84.45	6.27	8.67
Number of kernels per cob	475.80	324.34	760.98	97.42	20.48
Grain yield from a single cob (14% H_2O), g	155.02	115.90	206.61	21.86	14.10
Number of cobs per plant	1.04	0.89	1.43	0.08	7.38

4. Discussion

The alleviation in plants of stresses caused by abiotic as well as biotic factors is achieved by positively modulating the physiological attributes of crop plants, with a key role being the regulation of phytohormones and their signaling cascades [29]. This element acts at several levels in the plant. It can influence plant metabolism, physiology, and cellular functions [16]. Silicon stimulates antioxidant mechanisms, protects photosynthetic machinery, maintains ionic balance and nutrient uptake, promotes the production of secondary metabolites, enhances photosynthesis, reduces ROS, and helps chelate toxic metals. In addition, silicon modifies plant cell walls and regulates the expression of stress tolerance genes. Silicon has a multifaceted and beneficial effect on plant photosynthesis [30].

Calcium is an essential element for plant growth and development under stress and non-stress conditions. It determines cell wall and membrane stability and acts as a transmitter in many physiological processes, including the plant response to biotic stress [31]. Magnesium is an essential nutrient for many biochemical and physiological processes in plants. It is involved in chlorophyll synthesis, production, transport, and utilization of assimilates; enzyme activation; and protein synthesis [32]. Manganese is an important micronutrient for plant growth and development and sustains metabolic roles within different plant cell compartments. The metal is an essential cofactor for the oxygen-evolving complex (OEC) of the photosynthetic machinery, catalyzing the water-splitting reaction in photosystem II (PSII) [33].

The results of our own studies have shown that fertilization treatment significantly affects almost all the assessed physiological parameters in each measurement term. Previous studies on sugar beet have shown a significant effect of the foliar application of Si on the LAI, PAR absorption, and NDVI [34,35]. The foliar feeding of sugar beet with macro- and microelements has had a beneficial effect on the LAI, PAR absorption, and effective quantum efficiency value of Photosystem II (ΦPSII) and no significant effect on the remaining parameters of chlorophyll fluorescence and, after leaf adaptation to light, the stationary fluorescence and maximum fluorescence [36]. Foliar application of potassium silicate resulted in an increase in chlorophyll a and b and carotenoids in soybean plants [37]. Beneficial effects of foliar application of silicon-containing fertilizers on yield have been found in recent years for sugar beet [34,35,38,39], potato [40–43], wheat [44,45], white lupin [46], buckwheat [47], and soybean [37,48]. In previous studies, the most common increase in maize grain yield was achieved by Si fertilization in a range of 5–10% [49]. Our own research has shown that both soil fertilization with fertilizer containing Si and Ca and the separate foliar application of these elements, as well as a combined treatment of soil fertilization and foliar application, have a beneficial effect on maize grain yield. The best results were obtained using a treatment including both methods of Si fertilization. A soil application of fertilizer containing Si, Ca, and Mg contributed to an increase in grain yield of 34% compared to the control [50]. A beneficial effect on maize grain yield of soil fertilization with Zn and the foliar application of Si has been reported [51]. The three-time foliar application of a biostimulant containing Na_2SiO_3 and Fe alone, or in a treatment containing a fungicide, has been found to contribute to a significant increase in maize grain yield compared to a control with no biostimulant or fungicide protection [52]. Depending on the dose, the foliar application of K_2SiO_3 produced an increase in grain yield from 18% to 28% [53], and the foliar application of orthosilicic acid with choline and Ca has contributed to an increase in grain yield of 29.2% compared to the control [54]. The foliar application of K_2SiO_3 at a concentration of 1000 ppm has produced the highest sweet maize grain and biomass yields, this treatment being most effective under water-deficit conditions [55]. Increasing doses of foliar fertilizer with silicon (Herbagreen) increased maize grain yield. The best increase (by 38%) was obtained in the variant with the highest dose of this product (0.94 kg ha^{-1}) [56]. Foliar application of various Si fertilizers (NanoSilicon, Kelik Potassium-Silicon, and Microvit-6 Silicon) in three variants—once at the 5th leaf stage of maize, once at the 7th–8th leaf stage, and twice (at the 5th leaf stage plus at the 7th–8th leaf stage)—increased maize grain yields by 37.5–39.3%. The best effect was achieved after the product NanoSilicon was applied twice, as well as after Microvit-6 Silicon was applied once at the 5th leaf stage [57]. The use of stabilized orthosilicic acid has resulted in an increase in maize grain yield, the scale depending on the application method. Fertilizer containing stabilized orthosilicic acid (30% H_4SiO_4) was applied at different times and by different methods: control (no silicon application), seed dressing before sowing, soil spraying before sowing, and crop spraying in the 5th–6th leaf stage (BBCH 15–16). With less rainfall in 2021, there was an increase in grain yield of 5.1 and 1.5% and a reduction of 5.9% in the last variant. In the following year, the yield increases were considerably higher and amounted to, respectively, 11.6, 12.0, and 32.8%, which the authors explain by the higher amount of rainfall [58].

An effect similar to that on grain yield has been obtained for biomass yield. The soil application of liquid K glass and solid K_2SiO_3 has produced an increase in the biomass of young maize plants of 20–30% [59]. The use of orthosilicic acid with the addition of microelements has increased the dry-matter yield of maize, depending on the dose, by 12.0% and 24.7% compared to the control [60]. The application to the soil of K_2SiO_3 during sowing has contributed to an increase in the aboveground mass and grain yield of spring barley and the yields of maize biomass for silage and soybean seeds. The greatest effect of 1 kg of silica (SiO_2) on these crops was determined at doses of 105, 92, and 76 kg SiO_2 ha^{-1}. A positive effect of the foliar application of Si fertilizers has also been obtained for soybeans. The greatest increase in yield, compared to the control, was obtained in soybeans, a smaller increase in maize for silage, and the smallest increase in spring barley [61]. In our study, fertilization had an inconclusive effect on grain moisture. The timing and method of silicon application in the form of stabilized orthosilicic acid had no significant effect on grain moisture [58]. The applied fertilization treatment mostly contributed to increasing the protein and fat contents and reducing the starch content in the grain. The use of stabilized orthosilicic acid resulted in an improvement in grain quality by increasing the protein and fat contents. Depending on the application method, the protein content in the grain increased from 10.8% to 11.5% (foliar application), 11.5% (dressing of seed grain), and 11.1% (soil application before sowing). Contrastingly, the fat content increased from 3.41% to 3.75%, 3.57%, and 3.91%, respectively [50]. The foliar application of marine calcite ($CaCO_3$) fertilizer (Herbagreen) in maize cultivation, along with a 30% reduction in the amount of NPK fertilization, resulted in the same protein and fat contents in the grain as with the full NPK dose [62].

In winter wheat, foliar application of Polist 18 N fertilizer with silicon (18% N, 2% SiO_2, and 0.7% K) caused an increase in the gluten content, value of sedimentation index, quality number, and dough development time [45]. Foliar application of potassium silicate increased fat and protein content in soybeans [37]. In our own studies, fertilization treatment in most cases has significantly affected the weight of 1000 grains, the grain density, and the number of grains per cob. The timing and method of application of silicon in the form of stabilized orthosilicic acid had no significant effect on the weight of 1000 grains and on the number of grains per cob [58]. The soil application of Si, Ca, and Mg fertilizers has contributed to an increase in the number of kernels per cob and in the starch content in the grain [50]. The foliar application of orthosilicic acid with choline and Ca has contributed to an increase in the grain yield per cob compared to a control [54]. Foliar feeding has had a positive effect on the quality of maize grain (moisture, protein, lipid, carbohydrate, fiber, and mineral contents) [7]. A three-fold foliar application of fertilizer with silicon had a positive effect on maize cob yield elements (maize cob length without kernels, lower, middle, and upper diameter, grain weight, and cob weight). A medium to very high correlation was observed between these elements and silicon application [63]. Foliar application of each of the three different Si fertilizers (NanoSilicon, Kelik Potassium-Silicon, and Microvit-6 Silicon) in three variants—once at the 5th leaf stage of maize, at the 7th–8th leaf stage, and twice (5th leaf plus 7th–8th leaf stage)—increased the number of grains per cob compared to the control variant. After application of the NanoSilicon product, the number of grains per cob increased by 13.6–26.7% compared to the control variant. It was most effective with a single application at the 7th–8th leaf stage of maize and a double application, which furthermore influenced a 28.4% increase in grain weight per cob relative to the control.

Kelik Potassium-Silicon and Microvit-6 Silicon increased this weight by 23.3–26.7% and the number of grains per cob by 10–19.3% [57].

The foliar application of Si has also had a beneficial effect on the mycotoxin content in the grain. The foliar application of Na_2SiO_3 with Fe, depending on the dose, has reduced the content of the mycotoxin DON in maize grain by 82.8–90.8% and the mycotoxin ZEA by 96.7–98.4% [64].

Silicon-based soil fertilizers are of natural origin and are therefore safe for the environment (soil and water). They can also, after undergoing the appropriate registration procedure, be used in the EU in organic farming, where the use of synthetic fertilizers is prohibited. By reducing the impact of abiotic and biotic stress factors, Si fertilizers support the action of basic macronutrients (NPK). Silicon-based fertilizers can be in a dusty form, which is more difficult to apply on many farms due to the lack of specialized equipment. This results in the need to granulate them, which increases production costs. Another problem is the low awareness among farmers of the benefits of silicon fertilization.

5. Conclusions

This study suggests that soil fertilization with a fertilizer containing Si, Ca, Mg, and Mn; foliar single application of a product containing Si and Ca; and a treatment combining both had a beneficial effect on maize grain yield in Central Poland. The highest grain yield was produced by soil fertilization using SiGS fertilizer at a dose of 500 kg ha^{-1} (an increase of 17.5%), SiGS at a dose of 300 kg ha^{-1} plus the foliar application of Barrier Si-Ca fertilizer at a dose of 1 dm^3 ha^{-1} (an increase of 16.4%), and SiGS at a dose of 500 kg ha^{-1} plus the foliar application of Barrier Si-Ca fertilizer at a dose of 1 dm^3 ha^{-1} (an increase of 17.8%). The increase in grain yield from the treatments with the 50% NPK dose was similar in scale (on average, 11.9%) to that with the 100% NPK dose (12.6%) in relation to the control treatments. It is necessary to conduct further studies in more locations to verify the results under different soil and climatic conditions. The research results obtained could be applied to maize production in Poland once SiGS fertilizer is approved for sale.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15040837/s1. Figure S1. Changes in NDVI in 2023 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S2. Changes in NDVI in 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S3. Changes in mean NDVI in 2023 and 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S4. Changes in LAI in 2023 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S5. Changes in LAI in 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S6. Changes in mean LAI in 2023 and 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S7. Changes in absorption of PAR in 2023 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S8. Changes in absorption of PAR in 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S9. Changes in mean absorption of PAR in 2023 and 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S10. Changes in SPAD in 2023 depending on NPK fertilization (A1, A2) and soil and foliar application (B1–B8) in three terms; Figure S11. Changes in SPAD in 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S12. Changes in mean SPAD in 2023 and 2024 depending on NPK fertilization (A1, A2) and soil and foliar application of silicon-based fertilizers (B1–B8) in three terms; Figure S13. Changes in mean NDVI, LAI, PAR absorption, and SPAD depending on year in three terms.

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