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Effect of Combined Silicon Application as a Seed Dressing and Foliar Fertilization on Morphophysiological Traits, Productivity and Grain Quality of Spring Wheat (*Triticum aestivum* L.) Under Varied Total Atmospheric Precipitation During Growing Seasons

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Abstract

This study evaluated the impact of an integrated approach to silicon application—using the product ZumSil for both seed treatment and foliar feeding—on the growth, yield, and grain quality of two spring wheat cultivars (Rusałka and Serenada) grown under conditions of insufficient precipitation. The research was conducted between 2020 and 2022 in Winna Góra, where a water deficit relative to the requirements of spring wheat was recorded in each growing season. The results clearly demonstrated that silicon improved the productivity of spring wheat, particularly under drought stress. The highest grain yield was achieved in the treatment involving both seed dressing and three foliar applications of silicon (B4). The average yield in this group was 5.31 t ha^{-1}, which was 16% higher than that of the control group (4.58 t ha^{-1}). The Rusałka cultivar exhibited a higher yield potential (5.05 t ha^{-1}) compared to Serenada (4.81 t ha^{-1}), with the highest yields recorded in 2022. The application of silicon also had a positive effect on the morphological traits of the plants. The most pronounced effect was observed with the combined application (B4), where root length reached 14.13 cm, compared to 11.01 cm in the control group. This suggests an enhanced capacity for the plants to take up water and nutrients during periods of drought. Furthermore, silicon contributed to the improvement of certain grain quality parameters. In treatment B4, the highest content of protein (13.59%), gluten (27.09%), and starch (66.55%) was recorded, along with the highest hectoliter weight (79.11 kg hL^{-1}). However, this effect was less pronounced than in the case of crop yield. The study results confirm that silicon is an effective agent for mitigating the negative impacts of drought stress in spring wheat. The greatest efficacy was achieved through the combined use of seed treatment and foliar fertilization, suggesting that silicon can be considered a valuable component of modern, sustainable wheat production technologies—aligned with the objectives of the European Green Deal and the "Farm to Fork" strategy.

Keywords: spring wheat; silicon; yield; nutrients

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1. Introduction

The "Farm to Fork" strategy assumes that by 2030 pesticide use will be halved and the use of mineral fertilizers reduced by 20% [1]. The successive withdrawal of active substances by the European Commission will make the protection of wheat very difficult. It is therefore necessary to look for other technologies that will prevent yield losses. One of them may be the application of products containing silicon. Silicon belongs to the group of elements that favorably mitigate biotic and abiotic stress factors [2–6].

Silicon (Si) is an element that positively influences the growth, development, and productivity of cultivated plants, especially cereals. Although it is not classified as an essential nutrient, numerous studies indicate that it enhances plant tolerance to both abiotic and biotic stresses, including drought, high temperatures, salinity, and pathogen pressure [7]. Its mechanism of action is primarily linked to the deposition of silica within cell walls, which increases tissue strength, reduces transpiration, and improves the efficiency of water and nutrient utilization. In the case of spring wheat (*Triticum aestivum* L.), the application of silicon can lead to an increased leaf assimilation area, higher chlorophyll content, and intensified photosynthetic processes, which ultimately results in higher yields [8]. Its role is particularly significant under conditions of low rainfall, where silicon improves plant water management and mitigates the effects of drought stress [2]. Research has shown that silicon application can increase the number of grains per spike, the thousand-grain weight (TGW), and overall grain yield compared to control treatments. The beneficial effect of silicon is also observed in relation to grain quality parameters [5]. Many experiments have demonstrated an increase in total protein content, improved grain uniformity, and higher bulk density of the grain. Silicon also contributes to more efficient nitrogen uptake and utilization, which can enhance the technological quality of grain intended for human consumption or animal feed [9]. Furthermore, under stress conditions, its application helps mitigate the decline in grain quality that often occurs during periods of drought or high temperatures throughout the grain-filling and ripening stages.

In tomato, foliar application of silicon reduced the reproductive performance of the leafminer *Liriomyza sativae*, indicating its potential contribution to plant protection against insect pests [10]. Poland is one of the largest cereal producers in the European Union. Among the Member States it ranks third (after France and Germany) in terms of harvested output. In the years in which the experiment was carried out, that is 2020, 2021 and 2022, 0.6, 0.9 and 0.9 million tonnes of spring wheat, respectively, were harvested in Poland. Yields per hectare averaged 4.17 t in 2020, 3.96 t in 2021 and 4.24 t in 2022 [11]. Because of the large sown area, the importance of wheat cultivation in Poland is very high; the cultivated area exceeds two million hectares. Winter wheat predominates, as it is the basic raw material for the milling and baking industry. The spring form of wheat is grown on an area of about 160 thousand ha. Owing to its relatively poorly developed root system, spring wheat has high soil and nutrient requirements [12]. This is the main reason for its lower ability to take up nutrients from the soil. It should be noted, however, that the intensity of root system development in spring wheat depends to a large extent on soil moisture and structure and on the sowing date.

Spring wheat finds the most suitable conditions for growth and yielding on deep soils with good physical properties, rich in nutrients, with a reaction close to neutral and sufficiently moist. The growth of spring wheat is initially slow, which additionally increases its sensitivity to drought. Therefore, in order to produce a high yield, it requires a soil that retains water well, that is, heavier soils. The lighter the soil, the more the yield depends on the amount and distribution of rainfall and on soil management. The highest and most reliable yields of spring wheat are obtained on chernozems, black earths, loess soils, deep rendzinas, medium and heavy alluvial soils and on loamy soils. These are typical soils of

the very good and good wheat complexes [12]. Because of the increasingly developing pro-ecological trend and the creation of sustainable agriculture, ever newer and more environmentally friendly products stimulating plant growth are being introduced to the market [6,13]. Soil drought, that is, a severe deficit of water available to plants, occurs in the absence of precipitation and induces stress in plants, i.e., a response to unfavorable growth conditions. It is estimated that drought stress reduces 75% of the world harvest of basic crop plants, and wheat yields are reduced by about 20% [14,15]. Field experiments carried out under the soil conditions of Poland indicate a beneficial effect of foliar and soil application of silicon (Si) on the yield of spring wheat both under moderate soil moisture and under water stress [16,17].

It is assumed that integrated silicon application in the form of stabilized orthosilicic acid (H_4SiO_4), including simultaneous seed dressing and multiple foliar applications at key developmental stages of spring wheat (*Triticum aestivum* L.), significantly increases the efficiency of the soil–plant–atmosphere system by stimulating root development, improving water management, and intensifying the physiological processes responsible for biomass and assimilate accumulation. Consequently, this leads to increased crop productivity, improved grain quality traits, and increased plant tolerance to drought stress occurring under conditions of limited rainfall. This effect will be more pronounced with combined silicon application than with single seed dressing or foliar application, with the magnitude of the response dependent on the genotype of the spring wheat variety. The integrated application of silicon in the form of stabilized orthosilicic acid, combining seed dressing and repeated foliar treatments, enhances drought tolerance mechanisms in spring wheat by improving root system architecture and physiological efficiency, thereby increasing grain yield, yield components, and technological grain quality under conditions of prolonged precipitation deficit, with the magnitude of response being cultivar-dependent.

2. Materials and Methods

2.1. Experimental Field

The field experiment was carried out in 2020–2022 at the Field Experimental Station in Winna Gora (52.2058° N, 17.4490° E, 86 m a.s.l). This is a field facility of the Institute of Plant Protection—National Research Institute, based in Poznań (IPP—NRI). They were conducted with four field replicates for traits studied over three years, and with ten replicates for traits studied over two years. The field experiment was conducted in a split-plot design. The first-order factor (A), assigned to the main plots, was spring wheat cultivar: A1—Rusałka and A2—Serenada (Strzelce Plant Breeding Sp. z o.o.—IHAR Group (Strzelce, Poland). The second-order factor (B), assigned to the subplots, was different application dates of the silicon preparation ZumSil (stabilized orthosilicic acid (H_4SiO_4)): B1—control (without ZumSil application), B2—seed dressing, B3—foliar application, and B4—seed dressing + foliar application. Grain yield, thousand grain weight (TGW), protein content, starch content, gluten content, and hectoliter weight were determined in all three years, whereas leaf length and root length were evaluated only in 2020 and 2021.

Certified seed material was used in the experiment, purchased each year from a seed center and treated with a seed dressing. Serenada is a class A spring wheat variety. It features a medium heading time and high tolerance to soil acidity. It possesses excellent quality parameters, including a very high protein content—rated 8 on a 9-point scale—and a wet gluten content rated 9 on the same 9-point scale. It is a medium-height wheat. Rusałka is a variety with a medium-early heading time that tolerates spring and summer droughts well. It is included in the National Register and is recommended for cultivation by COBORU (the Research Centre for Cultivar Testing) in almost all Polish provinces. This variety is highly productive and produces grain with excellent quality characteristics. In 2016, it was

the highest-yielding Class A wheat variety in Poland, reaching 104% of the reference yield. The grain consistently achieves high quality standards, even with limited agricultural inputs. The variety features a medium 1000-grain weight and high-quality grain parameters. It grows to a medium height, exhibits strong resistance to lodging, and shows good resistance to pre-harvest sprouting. When grown on poorer-quality soils, it remains highly productive, thanks to its robust overall health and strong resistance to fungal wheat diseases. The manufacturer of the product ZumSil® (Otwock, Poland) is Perma-Guard Agro, which operates under the brand name PGAgro. The company specializes in the development and implementation of silicon-based products for agriculture, fruit growing, and horticulture.

Seed dressing was carried out on the same day as the sowing of spring wheat. Sprays were applied three times, at three growth stages: at tillering (BBCH 26—Biologische Bundesanstalt, Bundessortenamt i Chemische Industrie), at the first node stage (BBCH 31), and the last silicon treatment was applied at the flag leaf stage (BBCH 39). Other agrotechnical operations, fertilization and standard pesticide protection were the same for all combinations. The experimental plots measured 1.5 m by 11 m, giving an area of 16.5 m^2 under study. The experiment on spring wheat with the use of a silicon-based preparation was established within the arable land belonging to the Winna Gora Field Experimental Station. An area of 2.1 ha was made available on the farm for the study. The two spring wheat cultivars that were the subject of the study were sown on the area provided.

The two spring wheat cultivars were dressed and sown on the same date. Sprays were applied to objects (B2) and (B4) on the same dates and at the same growth stages. Plant growth was assessed during the growing season. Plant height and root length of spring wheat were measured at the tillering stage. After harvest, a qualitative and quantitative analysis was performed. The analysis covered grain yield, thousand grain weight, starch, protein and gluten content, and the hectoliter weight of the grain. The rates and dates of application of the preparation in the experiment were determined by the growth stages of the plant (Table 1). In two combinations, the tested preparation was also used as a seed dressing. Dressing was carried out on the same day as sowing so that the seed material was fresh. ZumSil is a liquid preparation, so in order to dress the wheat seeds, misting was used at a rate of 300 mL 100 kg^{-1} of seed. Foliar treatments were carried out three times with ZumSil, at a rate of 0.3 L ha^{-1} each time. The first foliar treatment was applied at the tillering stage BBCH 25–26, the second at stage BBCH 31, i.e., at the first node stage. The third treatment was applied at BBCH 39, i.e., at the flag leaf stage. The spray volume was 200 L ha^{-1}. The sprays were applied with a compressed-air knapsack sprayer manufactured and certified by APORO. APORO is a Polish company based in Poznań that specializes in the design and manufacture of specialized equipment for the application of plant protection products, particularly for use in field trials, greenhouses, and scientific research. The company has been operating since 1989 and produces a range of equipment—including handheld, backpack, wheelbarrow-style, cart-mounted, and tractor-mounted sprayers—designed for the precise dosing of liquid treatment agents.

The dates of the treatments resulted from the growth stages of the crop and are given in Table 2. Sowing was carried out with a plot drill at a fixed seeding rate of 190 kg of spring wheat seed per hectare. The sprays were applied on three dates corresponding to the occurrence of the growth stages in the experimental field.

Table 1. Combinations and application rates of the preparation ZumSil in spring wheat.

No.	Fertilization Combinations	Application	Rates
B1	Control	No treatments	–
B2	Seed dressing	ZumSil	300 mL/100 kg of seed
B3	Spray	3 ZumSil treatments	0.3 L/ha
B4	Seed dressing and spray	ZumSil and 3 ZumSil treatments	300 mL/100 kg of seed 0.3 L/ha

Table 2. Dates of application of the preparation in spring wheat.

Treatment	Date of Treatment			BBCH Scale	Growth Stage
	2020	2021	2022		
Seed dressing	03.04.2020	02.04.2021	08.04.2022	00	Dry caryopsis
Treatment I	07.05.2020	05.05.2021	06.05.2022	24–26	Full tillering
Treatment II	15.05.2020	11.05.2021	12.05.2022	31	First node
Treatment III	01.06.2020	31.05.2021	30.05.2022	39	Flag leaf

2.2. Meteorological Conditions of the Study

The values of precipitation measurements and mean air temperatures given in Table 3 refer to the weather conditions recorded at the meteorological station located at the Winna Gora Field Experimental Station and operated by the company AsterGate, based in Krakow.

Table 3. Monthly meteorological data from the Winna Gora Field Experimental Station—AsterGate data.

Month	Mean Air Temperature [°C]			Sum of Monthly Precipitation [mm·m^{-2}]		
	2020	2021	2022	2020	2021	2022
March	5.27	4.31	4.20	22.40	17.00	12.00
April	9.59	6.72	7.94	3.20	22.00	23.10
May	11.89	12.84	14.84	54.10	60.90	51.20
June	18.29	20.62	19.81	120.20	16.60	60.60
July	18.85	21.26	19.82	41.90	19.60	29.80

Table 4 presents monthly data which clearly show that the sum of precipitation falling in the growing season of spring wheat departed from the averages for the Środa district region, both in relation to the optimum precipitation totals and in relation to the long-term periods 1981–2010 and 1991–2020. According to COBORU guidelines, the water requirement of spring wheat from sowing to harvest should amount to 250 mm·m^{-2}. This means that there is a water deficit between the actual precipitation in the years of the experiment and the optimum precipitation recommended by Dzieżyc et al. [18]. The analysis of monthly precipitation also shows that spring wheat experienced a water deficit in practically every period and growth stage.

The long-term results showed that significant water deficits occurred during the period of the experiment. This may suggest that the climate in our region is changing towards warmer and drier conditions [19]. Table 5 contains information on the measurements of the mean monthly temperature in the years of the experiment compared with the long-term means. The results obtained from the meteorological station and from the long-term records kept by the Institute of Meteorology and Water Management—National Research Institute

in Poland (IMWM—NRI) show that the mean monthly temperature during the period of the experiment is higher than the long-term means for both 1991–2020 and 1981–2010 (Table 5). This applies in particular to June and July, when the grain yield of spring wheat is formed.

Table 4. Monthly precipitation compared with the long-term means, in mm·m^{-2}.

Precipitation	Year			Long-Term Mean	
	2020	2021	2022	1991–2020	1981–2010
March	22.40	17.00	12.00	40	35
April	3.20	22.00	23.10	30	35
May	54.10	60.90	51.20	60	60
June	120.20	16.60	60.60	55	55
July	41.90	19.60	29.80	85	75

Table 5. Mean temperature of the growing season compared with the long-term means [°C].

Temperature	Year			Long-Term Mean	
	2020	2021	2022	1991–2020	1981–2010
March	5.27	4.31	4.20	3.7	3.5
April	9.59	6.72	7.94	9.2	8.0
May	11.89	12.84	14.84	14.5	12.3
June	19.29	20.62	19.81	18.2	17.5
July	19.85	21.26	19.82	19.8	19.5

2.3. Soil Conditions of the Study

The area of the Winna Gora Field Experimental Station covers 97 hectares divided into blocks, for which soil tests were carried out separately. The tests were performed by a professional company so that the site of each of the research experiments could be characterized precisely. The block on which the experiment was established should be classified as sandy loam in soil quality class III a, that is, good arable soils. The organic matter content was 1.34%, which—in relation to the Wielkopolska region, where the average is 1.99%, and to the average for Poland of 2.2% [20]—shows that the soil fertility at the site of the experiment is below average. The soil reaction of 5.6 in pH(KCl) allows the soil to be classified as slightly acidic. The percentage particle size composition was also determined for the area on which the experiment was established: sand 2.0–0.05 mm (66.29%); silt 0.05–0.002 mm (30.7%); clay < 0.002 mm (3.63%). An area of about 2 hectares was reserved for the experiment, where a full crop rotation was maintained so that the forecrop was always winter oilseed rape. This is one of the better forecrops, because it leaves the field early and leaves a site rich in nutrients. For spring wheat, the time at which the forecrop leaves the field is not as important as the quality of the field left after the harvest of the preceding crop, and as ensuring the same conditions in successive years of the experiment [12].

2.4. Agrotechnical Conditions of the Study

The individual standard agrotechnical operations carried out in the experiment on all spring wheat cultivars in the successive years are listed in Table 6.

Table 6. Agrotechnical operations carried out as standard in the experiment with spring wheat.

	Agrotechnical Operations	Amount/Rate	Detailed Remarks
Autumn	Disc harrow	1 × diagonally	
Autumn	Winter plowing	25 cm	
Early spring	Drag harrow		To limit evaporation
Spring	Polifoska 6 fertilizer NPK-6,20,30 S-7	250 kg ha^{-1}	N 15 kg ha^{-1} P 50 kgha^{-1} K 75 kg ha^{-1} S 17.5 kg ha^{-1}
Spring	Urea 46% fertilizer	110 kg ha^{-1}	N 50.6 kg ha^{-1}
Spring	Cultivation 1 × diagonally		
Spring	Pre-sowing cultivation		
April	Sowing of the wheat cultivars	190 kg ha^{-1}	
May	Herbicide: Mustang Forte 195 SC + Atpolan 80 EC	0.8 L ha^{-1} 1.0 L ha^{-1}	
May	Insecticide: Cyperkil Max 500 EC	0.05 L ha^{-1}	
May	Fertilizer: ammonium nitrate 34%	150 kg ha^{-1}	N 51 kg ha^{-1}
May/June	Fungicide: Yamato 303 SE	1.7 L ha^{-1}	

2.5. Observations and Measurements

Parameter measurements and observations in the experiment were made both under field conditions—these include plant height measurements and yield—and under laboratory conditions, where leaf length and root length, TGW, protein, starch, gluten and grain density were determined. The analysis was carried out in the laboratory located at the Winna Gora Field Experimental Station.

2.5.1. Plant Height

Plant height [cm] of spring wheat was measured at the tillering stage. Ten consecutive plants were taken from each plot. The measurement was made in the analytical laboratory. From the measurements of 10 plants, a mean height was derived for the plot. The mean for the experimental object was obtained after determining the mean for the 4 plots corresponding to a given combination.

2.5.2. Grain Yield

The wheat was harvested with a Wintersteiger Classic 1540-41 plot combine (Ried im Innkreis, Austria). Each experimental plot was harvested in its entirety and the grain yield from the area under study was determined by weight. A sample weighing one kilogram was taken for laboratory analysis. In further calculations, the yield from the plot area was converted to yield per hectare. This was calculated from the proportion: plot yield × area of one hectare divided by plot area.

2.5.3. Thousand Grain Weight

Thousand grain weight was determined in the laboratory. A seed counter from ZBPP Sp. z o.o. SADKIEWICZ (Bydgoszcz, Poland) and a Sartorius BP 2100S balance (Göttingen, Germany) with an accuracy of 0.01 g were used for this purpose. The seed counter counts a defined, preset number of seeds. In this case, a sample of 500 seeds was counted. Three such counts were made from each sample. Each sample was weighed, the results were summed and divided by the number of samples. In this way, the mean weight of 500 seeds was obtained. This figure multiplied by 2 gave the weight of 1000 grains. After summing the 4 plots of one combination and dividing by the number of combinations, the mean thousand grain weight for the individual combinations was obtained.

2.5.4. Determination of Protein, Starch and Gluten Content and of Grain Density

The analysis of quality parameters such as protein, starch, gluten and hectoliter weight, also referred to as grain density, was carried out in the laboratory on an Infratec 1241 analyzer from FOSS (Hillerød, Denmark). This device is a transmission spectrometer operating in the near-infrared. A 0.5 kg sample of unground grain was used for the analysis. Analysis on this instrument makes it possible to obtain several parameters simultaneously. After the hopper has been filled, the analyzer performs an analysis of 10 subsamples, from which the mean for the analyzed sample is calculated automatically. In this way, 4 results were obtained for each combination. For the study, the mean of the analyzed samples was calculated for each experimental object. The method is based on the use of the absorption properties of electromagnetic radiation by protein, starch and gluten. The device also has a built-in analytical balance, which made it possible to obtain grain density results.

2.5.5. Biometric Analysis of Plants

The analysis of plant height and root length [cm] at the tillering stage was carried out in the analytical laboratory. Ten consecutive plants were taken from the field from each plot. The plants were rinsed free of soil residues and dried. Studies of these traits were conducted over only two years: 2020 and 2021. When interpreting the obtained results, it should be taken into account that the study was conducted over a period of only two years, which may limit the representativeness of the observed relationships in a broader temporal context. Consequently, caution should be exercised when extrapolating these findings to other environmental conditions or to years with different weather patterns.

Root length was measured with a calibrated flat linear rule graduated every 1 mm. The result for a plot is the sum of root lengths divided by the number of plants. The mean for the experimental object is the sum of the mean root lengths from the four plots assigned to a given combination divided by the number of plots. The analysis of leaf length was carried out in an analogous way.

2.5.6. Statistical Methods

The results were analyzed using analysis of variance (ANOVA) for a split-split-plot design [21]. The field experiment in each year followed a split-plot arrangement. However, for the combined analysis of data collected over three years or two years, year was introduced as an additional level in the hierarchical structure of the model. Consequently, the combined dataset was analyzed using a model corresponding to a split-split-plot design, with years treated as first-order units, spring wheat cultivar (factor A) as second-order units, and the application dates of the silicon preparation (factor B) as third-order units.

In the split-split-plot design, the mathematical model of the observations has the following form:

$$y_{ijkl} = \mu + \gamma_i + \alpha_j + \theta_{ij} + \beta_k + (\alpha\beta)_{jk} + \vartheta_{ijk} + \varphi_l + (\alpha\varphi)_{jl} + (\beta\varphi)_{kl} + (\alpha\beta\varphi)_{jkl} + \varepsilon_{ijkl}, \quad (1)$$

where

y_{ijkl}—observation obtained in the i-th block, for the j-th level of the year factor, the k-th level of factor A and the l-th level of factor B,
μ—general mean,
γ_i—random effect of the i-th block ($i = 1, 2, 3, 4$ or $i = 1, 2, \ldots, 10$),
α_j—effect of the j-th level of the year factor ($j = 1, 2, 3$ or $j = 1, 2$); the number of years depended on the trait analyzed,
θ_{ij}—random error effect of first-order units,
β_k—effect of the k-th level of factor A ($k = 1, 2$),
$(\alpha\beta)_{jk}$—effect of the interaction of the year factor and factor A,
ϑ_{ijk}—random error effect of second-order units,
φ_l—effect of the l-th level of factor B ($l = 1, 2, 3, 4$),
$(\alpha\varphi)_{jl}$—effect of the interaction of the year factor and factor B,
$(\beta\varphi)_{kl}$—effect of the interaction of factor A and factor B,
$(\alpha\beta\varphi)_{jkl}$—effect of the interaction of the year factor, factor A and factor B,
ε_{ijkl}—random error effect of third-order units.

Before carrying out the analysis of variance (ANOVA), the basic assumptions of the statistical model were verified, comprising the normality of the distribution of residuals and the homogeneity of variance. The Shapiro–Wilk test was used to assess normality, while the homogeneity of variance was checked with Levene's test.

The significance of the effect of the factors studied and of their interactions was assessed on the basis of analysis of variance. Where a significant effect of the main effects or of the interactions was found, the means were compared using Tukey's HSD test.

All calculations were performed using the STATISTICA package (version 13.3; TIBCO Software Inc., Palo Alto, CA, USA) and Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA). The statistical analyses were carried out at a significance level of $\alpha = 0.05$.

3. Results

3.1. Grain Yield

Analysis of the mean values of yield and thousand grain weight (TGW) showed a significant effect of the years of study and of the experimental factors on the formation of these traits (Tables 7, S1 and S2). As regards the years of study, the highest grain yield was obtained in 2022, where it amounted to 5.84 t ha^{-1}. This value was significantly higher than in 2020 and 2021, for which 4.44 and 4.51 t ha^{-1}, respectively, were recorded. TGW, on the other hand, did not differ significantly between years, reaching values from 34.96 to 35.96 g. Analysis of factor A (cultivar) showed that cultivar Rusałka (A1) was characterized by a higher grain yield and a higher thousand grain weight than cultivar Serenada (A2). The mean grain yield for cultivar Rusałka (A1) was 5.05 t ha^{-1} and was significantly higher than that obtained for cultivar Serenada (A2) (4.81 t ha^{-1}). A similar relationship was found for TGW, which reached 38.49 g for cultivar Rusałka (A1), while for cultivar Serenada (A2) it was only 32.44 g. With respect to factor B, differentiation was found in both grain yield and TGW. The highest grain yield was obtained for level B4 (5.31 t ha^{-1}), which significantly exceeded the remaining variants. A slightly lower grain yield was recorded for level B2 (5.03 t ha^{-1}), while for B3 and B1 it was 4.80 and 4.58 t/ha, respectively. In terms of TGW,

the highest value was likewise obtained in object B4 (36.31 g) and the lowest in object B1 (34.74 g). Variant B2 was characterized by an intermediate TGW value (35.58 g) and did not differ significantly from some of the remaining levels, while for B3 a value of 35.24 g was found. The grain yield of spring wheat was significantly differentiated depending on the interaction of the year of study and the cultivar. The highest grain yield was obtained in 2022 for cultivar A1, amounting to 6.08 t ha^{-1}, and was significantly higher than the yields obtained in the remaining combinations. Cultivar A2 (Serenada) in the same year reached a yield of 5.59 t ha^{-1}, significantly lower than that of cultivar A1 but higher than the values recorded in 2020 and 2021. In 2020 and 2021, the yielding of both spring wheat cultivars was similar and ranged from 4.42 to 4.60 t ha^{-1} (Table 8). The results obtained indicate a beneficial effect of the conditions prevailing in 2022 on the yielding of spring wheat, particularly of cultivar A1, which showed the highest yield-forming potential among the cultivars studied.

Table 7. Mean values of grain yield and TGW for years and for the individual experimental factors.

Factors	Levels of Factors	Grain Yield [t ha^{-1}]	TGW [g]
Y	2020	4.44 ± 0.39 b	34.96 ± 2.95 a
	2021	4.51 ± 0.40 b	35.48 ± 3.27 a
	2022	5.84 ± 0.46 a	35.96 ± 3.88 a
A	A1	5.05 ± 0.86 a	38.49 ± 1.38 a
	A2	4.81 ± 0.64 b	32.44 ± 1.56 b
B	B1	4.58 ± 0.71 d	34.74 ± 3.28 b
	B2	5.03 ± 0.73 b	35.58 ± 3.27 ab
	B3	4.80 ± 0.76 c	35.24 ± 3.48 b
	B4	5.31 ± 0,70 a	36.31 ± 3.49 a

Data are presented as means ± standard deviations (SD). Sample size: n = 96. Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

Table 8. Grain yield [t ha^{-1}] depending on the interaction of years and spring wheat cultivar.

A	Year		
	2020	2021	2022
A1	4.46 ± 0.50 c	4.60 ± 0.43 c	6.08 ± 0.43 a
A2	4.43 ± 0.27 c	4.42 ± 0.35 c	5.59 ± 0.36 b

Data are presented as means ± standard deviations (SD). Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

3.2. Morphological Traits of the Plants

In the analysis of leaf length, no significant effect of the year of study was found, since the mean values obtained in 2020 (20.53) and 2021 (20.07) were assigned the same letter. Factor A (cultivar) significantly differentiated leaf length, as cultivar A2 (21.50) was characterized by a significantly higher value of this trait than cultivar A1 (19.11). Factor B also affected leaf length. The highest mean value was recorded for level B2 (21.32) and the lowest for B1 (19.45). Level B3 (20.45), marked with the letters "ab", did not differ significantly either from the objects marked with the letter "a" or from those marked "b". In the case of root length, a significant effect of the year of study was found, since in 2021 a significantly greater mean root length (12.92) was obtained than in 2020 (12.56). Factor A (cultivar) did not differentiate this trait significantly, as the values for cultivar A1 (12.68) and cultivar A2 (12.80) belonged to the same homogeneous group. Factor B, on the other hand, significantly affected root length. The highest value was obtained for level B4 (14.13)

and the lowest for B1 (11.01). Level B2 (13.37), marked with the letters "ab", did not differ significantly from levels B4 and B3 (Tables 9, S3 and S4). Overall, it can be stated that the year of study affected only root length; factor A significantly influenced leaf length alone, whereas factor B significantly differentiated both leaf length and root length. Analysis of the interaction of factors A and B showed significant differentiation of mean leaf length between the combinations studied. For cultivar A1, the smallest leaf length was recorded for combination B1 (15.52), which differed significantly from the remaining objects in this group. Combinations B2 (19.74), B3 (20.60) and B4 (20.59) formed a homogeneous statistical group and did not differ significantly from one another. For cultivar A2, the highest leaf length values were obtained in combinations B1 (23.38) and B2 (22.91), between which no significant differences were found. These values were significantly higher than those obtained for combinations B3 (20.30) and B4 (19.40), which likewise did not differ significantly from each other. The greatest mean leaf length was found in combination A2 × B1 (23.38) and the smallest in combination A1 × B1 (15.52). The results obtained indicate the occurrence of an interaction between the factors studied, since the response of leaf length to changes in the level of factor B varied depending on the level of factor A (cultivar) (Table 10).

Table 9. Mean values of leaf length and root length for years and for the experimental factors.

Factors	Levels of Factors	Leaf Length [cm]	Root Length [cm]
Y	2020	20.53 ± 3.11 a	12.56 ± 2.44 b
	2021	20.07 ± 2.95 a	12.92 ± 2.51 a
A	A1	19.11 ± 2.89 b	12.68 ± 2.40 a
	A2	21.50 ± 2.70 a	12.80 ± 2.56 a
B	B1	19.45 ± 4.57 b	11.01 ± 2.14 c
	B2	21.32 ± 2.48 a	13.37 ± 2.23 ab
	B3	20.45 ± 1.93 ab	12.44 ± 2.57 b
	B4	19.99 ± 2.20 b	14.13 ± 1.82 a

Data are presented as means ± standard deviations (SD). Sample size: n = 160. Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

Table 10. Mean values of leaf length [cm] for the A × B combinations.

B	A	
	A1	A2
B1	15.52 ± 2.30 c	23.38 ± 2.26 a
B2	19.74 ± 1.93 b	22.91 ± 1.89 a
B3	20.60 ± 1.58 b	20.30 ± 2.26 b
B4	20.59 ± 2.15 b	19.40 ± 2.13 b

Data are presented as means ± standard deviations (SD). Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

In the years analyzed, leaf length was significantly differentiated depending on the combinations of factors A and B studied. In 2020, the greatest mean leaf length was recorded for combinations A2 × B1 (23.31) and A2 × B2 (23.27), which formed a homogeneous statistical group. High values were also obtained for combinations A1 × B4 (21.33), A2 × B3 (21.23) and A1 × B3 (21.21), although these did not differ significantly from some of the remaining objects. The shortest leaves were characteristic of combination A1 × B1 (15.70), which differed significantly from most of the variants analyzed. A low value was also found for combination A2 × B4 (18.12). In 2021, the highest mean leaf length was again

obtained for combination A2 × B1 (23.44), with a slightly lower value for A2 × B2 (22.55). These objects belonged to the groups with the highest values of the parameter studied. The shortest leaves, as in the previous year, occurred in combination A1 × B1 (15.34), which differed significantly from the objects with the greatest leaf length. The remaining combinations reached intermediate values, ranging from 19.36 to 20.68. A comparison of the results from both years indicates that in most combinations leaf length was slightly smaller in 2021 than in 2020. The exceptions were combinations A2 × B1 and A2 × B4, for which an increase in the value of the parameter studied was recorded. Regardless of the year of study, the greatest leaf lengths were obtained for combinations A2 × B1 and A2 × B2, while the shortest leaves were consistently observed in combination A1 × B1. The results therefore indicate that level A2, particularly in combination with levels B1 and B2, favored the formation of greater leaf length (Table 11).

Table 11. Mean values of leaf length [cm] for the Y × A × B combinations.

A	B	Year	
		2020	2021
A1	B1	15.70 ± 2.60 e	15.34 ± 2.08 e
	B2	20.10 ± 1.91 bcd	19.38 ± 1.99 cd
	B3	21.21 ± 1.55 abcd	19.99 ± 1.43 bcd
	B4	21.33 ± 2.43 abc	19.84 ± 1.61 bcd
A2	B1	23.31 ± 1.20 a	23.44 ± 3.05 a
	B2	23.27 ± 2.18 a	22.55 ± 1.57 ab
	B3	21.23 ± 2.21 abc	19.36 ± 1.99 cd
	B4	18.12 ± 2.01 de	20.68 ± 1.39 abcd

Data are presented as means ± standard deviations (SD). Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

3.3. Nutrient Content and Grain Density

Analysis of the results presented in Table 12 showed a significant effect of both the year of study and the experimental factors on grain quality (Tables S5–S8). Protein content was highest in 2020 and amounted to 13.48%, while the lowest value was recorded in 2021 (13.06%). In 2022, protein content reached an intermediate level (13.32%). In the case of starch, the highest values were found in 2020 and 2021, 66.51% and 66.11%, respectively, and these did not differ significantly. The grain harvested in 2022 was characterized by a significantly lower starch content (64.99%). The highest gluten content was obtained in 2021 (26.73%), whereas 2020 and 2022 did not differ significantly in this respect, reaching 26.08% and 25.80% respectively. Hectoliter weight, in turn, was lowest in 2020 (77.35 kg hL^{-1}), and higher, statistically similar values were recorded in 2021 and 2022, 78.86 and 79.04 kg $hl^{-1,}$ respectively. Factor A (cultivar) also significantly differentiated all the traits analyzed. Cultivar A1 was characterized by a higher content of protein (13.46%), starch (66.12%) and gluten (26.47%) and by a higher hectoliter weight (78.52 kg hL^{-1}) than cultivar A2, for which the values of these parameters were 13.11%, 65.63%, 25.95% and 78.31 kg hL^{-1}, respectively. Among the levels of factor B, the most favorable results were obtained for variant B4, which was characterized by the highest content of protein (13.59%), starch (66.55%) and gluten (27.09%), as well as by the highest hectoliter weight (79.11 kg hL^{-1}). The least favorable values of most of the parameters assessed were found for level B1, where protein content was 13.08%, starch 65.16%, gluten 25.40% and hectoliter weight 77.84 kg hL^{-1}. Levels B2 and B3 occupied an intermediate position with respect to all the grain quality traits analyzed. Analysis of the interaction of the year of study and factor A showed significant differentiation of the grain quality traits studied. The highest starch content was recorded in combinations

A1 in 2021 (67.56%) and A2 in 2020 (67.43%), which did not differ significantly from each other. The remaining combinations were characterized by a lower starch content, ranging from 64.67 to 65.60%, and belonged to one homogeneous group. The results obtained indicate that the effect of the factor studied on starch content varied depending on the conditions prevailing in the individual years of study. In the case of gluten content, the highest value was found for cultivar A1 in 2021, where it amounted to 27.33%. This result was significantly higher than all the remaining values. The remaining combinations did not differ significantly from one another, and gluten content ranged from 25.80 to 26.28%. This means that only in 2021 did the use of cultivar A1 favor a significant increase in the gluten content of the grain. Analysis of grain density expressed as hectoliter weight showed that the highest values were obtained for cultivar A2 in 2021 and 2022, reaching 79.28 and 79.36 kg hL^{-1}, respectively. These values did not differ significantly. The lowest hectoliter weight, on the other hand, was found for cultivar A2 in 2020, where it amounted to 76.28 kg hL^{-1} and was significantly lower than the remaining results. Cultivar A1 in all years of study and cultivar A2 in 2020 formed an intermediate group with respect to the value of this trait (Table 13). Analysis of the mean gluten values showed differentiation of the results depending on the combinations of factors A and B studied and on the year of study. In 2020, gluten content ranged from 23.75% to 27.43%. The highest value was recorded for combination A1 × B4 (27.43%) and the lowest for A2 × B1 (23.75%). Combination A1 × B4 belonged to the group with the highest gluten values, whereas A2 × B1 was characterized by a significantly lower content of this component. In 2021, a general increase in gluten content compared with the previous year was found. The highest mean value was again obtained for combination A1 × B4, which amounted to 28.65% and was the highest of all the results analyzed. High values were also recorded for combinations A1 × B2 (27.25%) and A1 × B3 (27.13%). The lowest values occurred for combinations A2 × B1 (25.90%) and A2 × B2 (25.95%); however, because of the overlapping letter designations, most of the combinations studied did not differ significantly. In 2022, the gluten values were more even than in the previous years and ranged from 25.08% to 26.55%. The highest gluten content was again characteristic of combination A1 × B4 (26.55%) and the lowest of A1 × B1 (25.08%). The letter designations indicate that there were no significant differences between most of the combinations (Table 14).

Table 12. Mean values of protein, starch, gluten and grain density for years and for the experimental factors.

Factors	Levels of Factors	Protein [%]	Starch [%]	Gluten [%]	Hectoliter [kg hL^{-1}]
Y	2020	13.48 ± 0.48 a	66.51 ± 1.47 a	26.08 ± 1.34 b	77.35 ± 1.22 b
	2021	13.06 ± 0.59 c	66.11 ± 1.59 a	26.73 ± 1.24 a	78.86 ± 0.86 a
	2022	13.32 ± 0.32 b	64.99 ± 1.18 b	25.80 ± 0.74 b	79.04 ± 0.88 a
A	A1	13.46 ± 0.53 a	66.12 ± 1.60 a	26.47 ± 1.21 a	78.52 ± 0.77 a
	A2	13.11 ± 0.47 b	65.63 ± 1.48 b	25.95 ± 1.13 b	78.31 ± 1.59 b
B	B1	13.08 ± 0.34 b	65.16 ± 1.86 c	25.40 ± 1.14 c	77.84 ± 1.20 c
	B2	13.23 ± 0.66 b	65.96 ± 1.40 ab	26.23 ± 0.97 b	78.45 ± 1.14 b
	B3	13.24 ± 0.44 b	65.82 ± 1.33 bc	26.10 ± 0.93 b	78.26 ± 1.14 bc
	B4	13.59 ± 0.51 a	66.55 ± 1.32 a	27.09 ± 1.13 a	79.11 ± 1.25 a

Data are presented as means ± standard deviations (SD). Sample size: n = 96. Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

Table 13. Mean values of starch content, gluten content and grain density for the Y × A combinations.

Y	A	Starch [%]	Gluten [%]	Hectoliter [kg hL^{-1}]
2020	A1	65.60 ± 1.30 b	26.28 ± 1.02 b	78.41 ± 0.46 b
	A2	67.43 ± 1.01 a	25.89 ± 1.61 b	76.28 ± 0.65 c
2021	A1	67.56 ± 0.67 a	27.33 ± 1.27 a	78.43 ± 0.79 b
	A2	64.67 ± 0.60 b	26.14 ± 0.91 b	79.28 ± 0.72 a
2022	A1	65.19 ± 1.57 b	25.80 ± 0.80 b	78.73 ± 0.98 b
	A2	64.79 ± 0.56 b	25.81 ± 0.70 b	79.36 ± 0.66 a

Data are presented as means ± standard deviations (SD). Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

Table 14. Mean gluten values [%] for the Y × A × B combinations.

A	B	Year		
		2020	2021	2022
A1	B1	25.78 ± 0.67 bcd	26.28 ± 0.62 bc	25.08 ± 0.33 cd
	B2	26.30 ± 1.10 bc	27.25 ± 1.27 abc	26.10 ± 0.43 bc
	B3	25.60 ± 0.34 bcd	27.13 ± 0.40 abc	25.48 ± 0.78 bcd
	B4	27.43 ± 0.84 ab	28.65 ± 1.42 a	26.55 ± 0.79 abc
A2	B1	23.75 ± 1.65 d	25.90 ± 0.70 bcd	25.65 ± 0.68 bcd
	B2	26.28 ± 1.01 bc	25.95 ± 0.57 bcd	25.53 ± 0.79 bcd
	B3	26.53 ± 0.67 abc	26.10 ± 1.47 bc	25.78 ± 0.68 bcd
	B4	27.03 ± 0.48 abc	26.63 ± 0.88 abc	26.28 ± 0.65 bc

Data are presented as means ± standard deviations (SD). Statistical significance was set at $p < 0.05$. Means followed by the same letter are not significantly different according to Tukey's HSD test.

4. Discussion

Research on the role of silicon (Si) in mitigating the effects of water deficit in plants is currently being conducted worldwide. Despite its high content in plants (0.1–10%), silicon is not regarded as an element essential for plants, but is classed among the beneficial elements. Silicon plays an important role in the mineral nutrition of plants, especially of species that accumulate this element in large amounts [22]. Field experiments carried out under the soil conditions of Poland indicate a beneficial effect of foliar and soil application of silicon on the yielding of spring wheat both under moderate soil moisture and under water stress [16,17]. Comparing the results obtained in the present study with the results published in the cited articles, it can be stated unequivocally that silicon has a significant effect on grain yield. A similar yield-forming effect after foliar application of silicon under conditions of soil moisture limited to 40% was obtained by Maghsoudi et al. [23] in spring wheat. The source of plant-available silicon was sodium silicate applied twice at a concentration of 6 mM Si·L^{1}. The drought-sensitive wheat cultivar responded to the treatments with an 18% increase in yield and the resistant cultivar with an increase of 11%. A similar effect was obtained by El-Mageed et al. [24] in maize. Supplying maize with silicon at 2 and 4 mM Si/L under 20% field water capacity also effectively increased the resistance of the plants to stress and limited the reduction in grain yield by 15 and 30%, respectively, relative to the yield of the object without Si. A similar effect in an experiment with maize was obtained by Gomaa et al. [25]. After two applications of Si in the form of potassium silicate (4.4 mM Si L^{-1}), grain yield increased by 16%, and after three applications by 25%. A single treatment, on the other hand, was ineffective. In the studies of Kowalska et al. [16], three sprays of wheat cultivar Harenda with liquid silicic acid under drought conditions increased grain yield by 23%. The results indicate a clear differentiation among the studied varieties in terms of their yield-formation strategies and root system development. The 'Rusałka' variety produced

a significantly higher yield compared to 'Serenada', demonstrating a greater production potential under the conditions of this study. Conversely, 'Serenada' exhibited a more highly developed root system than 'Rusałka'. These findings suggest distinct mechanisms for the allocation of assimilates between above-ground and below-ground organs. The higher yield of 'Rusałka' implies a preferential allocation of resources toward the development of generative parts and the creation of harvestable biomass, whereas 'Serenada' may have directed a larger share of its growth potential toward root development, thereby enhancing its capacity to uptake water and nutrients. This phenomenon confirms that more extensive root system development does not always translate directly into higher yields; rather, the production efficiency of a variety is determined by the balance between the growth of below-ground and above-ground organs, as well as the efficiency with which accumulated resources are utilized. Dicotyledonous plants deprived of access to water also respond to foliar silicon supply. Potassium silicate applied four times during the growing season of sugar beet limited the decrease in root yield under severe and moderate drought stress by 21 and 31% [26]. Artyszak et al. [27] also reported that combined foliar fertilization with calcium and silicon increased sugar beet root yield by approximately 21.8% compared with the control, without significantly affecting root sucrose content. In none of the experiments cited above, nor in the present study, did silicon supplied to plants growing at optimum moisture have an effect on yield level; the role of silicon became apparent under conditions of severe stress. Ma et al. [28] and Guevél et al. [29] state that this element is taken up mainly by plant roots in the form of H_4SiO_4, and that its translocation from leaves to roots is limited. According to Laane [4] and Othmani et al. [30], foliar sprays with sodium and potassium silicates are more effective against biotic stresses, and the silica layer formed in the leaves acts as a mechanical barrier preventing fungal infections [5,29]. The quality of spring wheat grain is a key factor determining its technological and feed value, as well as its suitability for food processing. In recent years, there has been growing interest in the use of silicon-based preparations in crop production, due to their beneficial effects on plant growth, development, and resistance to environmental stress [31]. Although silicon is not classified as an essential element for higher plants, numerous studies indicate that its application can significantly improve the quality parameters of wheat grain—particularly under conditions of drought, high temperature, or limited nutrient availability. The use of silicon-based preparations—whether through seed treatment or foliar application—influences the physiological processes responsible for yield formation and grain quality. Silicon enhances photosynthetic efficiency by improving plant water management and reducing excessive transpiration, which helps maintain high assimilation activity even during periods of water scarcity [32]. Consequently, the accumulation of assimilates in the spikes and developing grains increases. One of the most frequently observed effects of silicon is an increase in the total protein content of the grain. This phenomenon is linked to improved nitrogen uptake by the root system and more efficient utilization of this nutrient in metabolic processes [33]. A high protein concentration is crucial for the technological suitability of wheat, as it influences flour quality and the grain's baking value. Our own research has shown that the application of silicon—whether through seed treatment or foliar application—significantly increases the protein content in the grain of the spring wheat varieties studied. This effect points to the element's beneficial influence on nitrogen metabolism within the plants, as well as a more efficient utilization of nitrogen taken up from the soil. By affecting physiological and biochemical processes, silicon can enhance the activity of enzymes involved in nitrogen metabolism, thereby promoting the synthesis of amino acids and proteins. Consequently, the grain exhibits higher nutritional and technological value, which is particularly significant for the production of wheat intended for human consumption. These findings confirm that silicon fertilization

can be an effective component of spring wheat cultivation technology, aimed not only at increasing yields but also at improving grain quality. Research conducted under various climatic conditions also indicates that the application of silicon can increase wet gluten content and improve the Zeleny sedimentation value [34]. These parameters are among the primary indicators of the technological quality of wheat. A higher gluten content contributes to the formation of dough with greater elasticity and an improved ability to retain fermentation gases, which results in higher-quality baked goods [35]. Silicon also has a beneficial effect on the thousand-kernel weight (TKW) and grain uniformity. By enhancing plant resistance to stressors—such as drought, high temperatures, or pathogen pressure—silicon allows the grain-filling process to proceed more efficiently, leading to better-developed kernels [36]. Improvements in TKW and grain uniformity are significant for both the commercial value of the raw material and its milling yield. Chen et al. [37] studied the effect of soil supplementation with silicon in the form of potassium silicate at a rate of 300 mg Si kg^{-1} on the yields of two drought-sensitive rice cultivars. Water deficit in the pots was maintained for 15 days after sowing. After silicon uptake, shoot mass increased by nearly 100%, but only under stress conditions. Ullah et al. [38] investigated the effects of silicon dose and application timing on rice grown under different soil moisture conditions (100%, 75%, and 50% of field capacity). Silicon applied at 300 kg Si·ha^{-1} at different growth stages increased grain yield by 34–45% compared with the untreated control. In a pot experiment with oilseed rape (*Brassica napus* L. cv. Okapi), Habibi [39] found that soil application of sodium silicate at 0.35 g Na_2SiO_3·kg^{-1} soil increased shoot and root dry weight, relative water content, and photosynthetic rate under drought stress compared with plants receiving no silicon. The soil, with a pH of 6.8, showed a low content of plant-available Si (30 mg kg^{-1}). Soil moisture was limited for a period of 25–40 days after sowing. Under stress conditions, the shoot mass of oilseed rape was 75% higher in the object supplied with silicon than in the object without Si. Under good irrigation, silicon did not differentiate yields. Melon growing under a moderate water deficit (50% field water capacity) also responded to soil application of increasing rates of silicic acid with a progressive increase in yield [40]. The effectiveness of silicon in soil application can be high, particularly at a low content of plant-available Si. The role of silicon nutrition in crop improvement has also been reviewed by Artyszak and Kucińska [41]. The research shows that the yield-forming potential of silicon depends on the form and method of its application, on the plant species and cultivar, on the rate and availability of silicon from the fertilizer used (diatomaceous earth, calcium, sodium or potassium silicate and others), on the silicon concentration in the solution for foliar application, on the number and timing of the treatments, on the soil type and pH, and on the degree of stress occurring [4,30,42]. Diatomaceous earth has also been investigated as a source of silicon in onion cultivation [43]. As can be seen in the scientific papers cited, the results obtained in various crops with respect to silicon application indicate an effect on plant yielding. The same conclusions were also drawn in the present study. It can also be noted that silicon is an element whose positive effect is manifested under stress conditions. The present study showed that a water deficit occurred during the conduct of the experiment. The results confirmed the positive effect of silicon application on plant yielding and development, as in the publications cited above. In the articles referred to above, not only yield but also other parameters were compared. In each case, whether in wheat, sugar beet, rice or oilseed rape, the results showed a significant effect or tendencies that had a positive influence on the development and yielding of the plants studied. In the present study, carried out in 2021 at the Field Experimental Station, the results of the quantitative and qualitative analysis were similar. The application of silicon had an effect from the very beginning of the growing season. Although the plants of one of the spring wheat cultivars showed lower initial growth, at a later growth stage they

proved to be larger. It can be concluded that the plants in which silicon was applied as a seed dressing developed their root system to a greater extent, which gave better results at a later date. Differences in grain yield were also observed among the silicon application dates. Other parameters studied, if they did not show a significant positive response to silicon application, showed positive tendencies. Application as a seed dressing, foliar application and the combination of foliar application and seed dressing all gave positive effects. Two spring wheat cultivars were used in the present experiment. After analyzing the results, it can be concluded that the cultivar may be of considerable importance in the response to silicon application. On the basis of the analysis of the results of the present experiment, this statement can readily be related to the results obtained in the article "Response of spring wheat growing under drought stress to foliar and soil application of silicon" by Urszula Sienkiewicz-Cholewa of the Institute of Soil Science and Plant Cultivation—State Research Institute in Wrocław (2021).

5. Conclusions

The application of silicon (Si) significantly increased the grain yield of spring wheat under drought stress conditions. The highest yield was obtained in the combination comprising seed dressing and three foliar sprays with the preparation ZumSil (B4), reaching an average of 5.31 t ha^{-1} as against 4.58 t ha^{-1} in the control object. The combined application of silicon as a seed dressing and as a foliar treatment stimulated root system development most effectively. Variant B4 was characterized by the greatest root length (14.13 cm), which indicates an improvement in the ability of the plants to take up water and nutrients under conditions of limited moisture availability. The response of spring wheat to silicon application depended on the cultivar. Cultivar Rusałka (A1) achieved a higher grain yield (5.05 t·ha^{-1}) and better grain quality parameters than cultivar Serenada (A2), which indicates genotypic differentiation in the efficiency of silicon use. Silicon had a beneficial effect on the technological quality of the grain, although this effect was weaker than in the case of yield. In variant B4, the highest content of protein (13.59%), gluten (27.09%) and starch (66.55%) and the highest hectoliter weight of the grain (79.11 kg hL^{-1}) were found, indicating a tendency towards improvement of the quality parameters. The effectiveness of silicon was particularly evident under the water deficit conditions that occurred throughout the study period. The results obtained confirm the role of silicon as a factor mitigating the effects of abiotic stress, increasing the resistance of plants to drought and stabilizing the yield level under conditions of limited water availability. The results obtained indicate that silicon is highly effective in mitigating the effects of drought stress in spring wheat; however, this issue requires further, in-depth research. Future studies should include a broader range of wheat varieties, which would allow for a more precise determination of genotypic differences in the efficiency of silicon uptake and utilization, as well as the identification of varieties best adapted to water-deficient conditions. Another area for future research should be the determination of optimal silicon application rates and timing, based on prevailing weather conditions and the developmental stages of the plants. It would be particularly valuable to investigate which developmental stages of wheat are most responsive to silicon, and to what extent the number of foliar applications influences its utilization efficiency. Furthermore, detailed analyses of the physiological and biochemical mechanisms underlying the increased drought tolerance of plants following silicon application are warranted. Such research could encompass the assessment of antioxidant enzyme activity, plant water relations, photosynthetic efficiency, the accumulation of osmoregulatory compounds, and the expression of genes associated with the response to abiotic stress. Future studies should also consider the interaction of silicon with other production practices, such as nitrogen fertilization, the use of biostimulants, or the application of micronutrients. This would

facilitate the development of comprehensive strategies to improve wheat productivity and grain quality while simultaneously reducing the reliance on chemical inputs. It would be particularly interesting to determine the potential for using silicon as a component of sustainable agriculture, supporting the objectives of the European Green Deal and the "Farm to Fork" strategy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16222330/s1, Table S1: Analysis of variance for grain yield; Table S2: Analysis of variance for TGW; Table S3: Analysis of variance for leaf length; Table S4: Analysis of variance for root length; Table S5: Analysis of variance for protein content; Table S6: Analysis of variance for starch content; Table S7: Analysis of variance for gluten content; Table S8: Analysis of variance for hectoliter weight.

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