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Methods of Silicon Application on Organic Spring Wheat (*Triticum aestivum* L. spp. vulgare) Cultivars Grown across Two Contrasting Precipitation Years

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Abstract: The potential of silicon used in two forms, two methods and three cultivars of spring wheat cultivated under organic farming conditions is high, as it helps plants to alleviate abiotic stresses. The research hypotheses of paper were the assumptions that the effectiveness of silicon may differ not only by the form of silicon and the method of its application, but also by the variety of common wheat and different water conditions in the soil during the growing season. These hypotheses were confirmed. The aim of this study was to determine the effectiveness of liquid and powder silicon forms and different methods of application in three cultivars (Harenda, Serenada and Rusałka) of spring wheat organically grown under a specific field experiment in water stress vs. no stress conditions. The water stress of plants was assessed on the basis of the sum of precipitation in the winter–spring and vegetation season in each year. The differences in water availability for the plants in the experimental years were confirmed. Silicon (Si) was used for seed dressing and/or for leaf spraying. In the first case, the powdered form of Si was used at a dose of 0.5 kg/100 kg of seeds; it was used together with the liquid form at a dose of 0.5 L/100 kg of seeds, and in the second, the liquid form of Si was used at a dose of 0.5 L per 200 L of water per hectare; spraying was carried out at the following plant development stages: three tillers detectable, the first node and the flag leaf. The application of Si positively influenced the wheat yield depending on the method of Si application, wheat variety and severity of water stress. The cultivar Harenda was more susceptible to lower water content in the soil than the cultivars Rusałka and Serenada. Under conditions of water stress, the use of Si slowed the development of young Harenda plants, but ultimately, the variety increased its grain yield to a greater extent than the other two varieties. The lowest weight of a thousand grains (TGW) was found in the Harenda variety; however, Si treatment improved this parameter. Si increased the yields of the three wheat varieties, and the highest were harvested in plots with combined Si treatments. The yields of the Rusałka and Serenada cultivars on these plots were 14 to 28% higher compared to the control. Harenda was the least fertile variety, but it increased its yield more than the other two varieties. This variety increased its yield in 2018 (year of average rainfall) by 26% from 2.92 to 3.94 tons per hectare, and in 2019 (a year of drought) by 42% from 1.66 to 2.87 tons per hectare. It can be concluded that Si improves the wheat yield, and its efficiency depends on the scale of water stress, the method of application and the variety. The simplest and most adaptable method of Si application is seed dressing and has prospects for wider application, especially in organic farming.

Keywords: diatomaceous earth; monosilicic acid; Si application method; soil water conditions; wheat cultivar

1. Introduction

Climate change, including rising temperatures and increasingly severe droughts, has hampered crop development and yields. Plants mitigate the effects of less soil water content using physiological mechanisms and produce bioactive compounds such as antioxidants and osmolytes. In the literature, the influence of ascorbic acid, glutathione and proline on the alleviation of the harmful effects of drought stress for plants is noted. Studies on the use of egozogenic antioxidants and proline are described; the synergistic effect of these substances is noted [1]. Proline has possible options for consideration as an indicator and a potential marker of clinical damage by osmotic stress; however, degradation and toxicity are potential threats posed by proline. Mycorrhizal plants and their non-mycorrhizal counterparts show varied expression patterns regarding proline [2].

Another of the alternative methods for alleviating negative stress effects might be application of silicon as a fertilizer (root or foliar application). An abundant mineral element in plant tissues, silicon (Si) provides structural support and improves tolerance to disease, drought, metal toxicity [3,4] and biotic stresses including plant pathogen and insect pests [5]. The excessive use of Si does not harm or pollute plants or corrode machinery [6]. Silicon is present in plants in amounts equivalent to those of macronutrient elements such as calcium, magnesium and phosphorus, and in grasses, often at higher levels than any other inorganic constituent [7]. Plants take up Si from soil solution both passively and actively and are unable to accumulate Si. Studies conducted about fifty years ago showed that species of Poaceae contained up to ten to twenty times more Si than non-monocotyledonous species [8]. More recent research on specimens from botanical gardens indicates that high Si accumulation is restricted to primitive plants and to some monocot clades, namely the Poaceae, Cyperaceae and Commelinaceae [9]. According to Sacała [10], many plants, particularly monocotyledonous species, contain large amounts of Si (up to 10% of dry mass). The role of Si in plants is not restricted to the formation of a physical or mechanical barrier (as precipitated amorphous silica) in cell walls, lumens and intercellular voids; silicon can also modulate plants' metabolism and alter physiological activities, particularly in plants subjected to stress conditions. However, in some plants, increased silicon application does not improve plant growth; a better understanding of the interactions between silicon application and plant responses will contribute to more efficient Si use, especially under stress conditions [10].

Usually, plants in natural conditions do not demonstrate Si shortages. Nevertheless, in crop production, fertilizers containing Si are often applied to crops such as rice and sugar cane to increase their yield and quality [11–13], but the positive effect of Si application is not restricted to monocotyledonous plants. In tests with collard, silicon suppressed the harmful effects of drought on leaf and root length. This suggests that monocots (e.g., *Triticum aestivum* L.) react to Si application similarly to non-monocot plant species (e.g., *Brassica oleracea*) [14]. Another advantage is that Si application increases the respiration of soils deficient in phosphorous. A major component in regulating P mobilization in Arctic soils, Si is assumed to play a role in the management of P availability in all types of soils [15].

Silicon has been widely reported to improve the growth, biomass, yield and quality of a wide variety of crops including monocotyledonous crops such as wheat, rice, maize and barley. The observed increases in grain yield, however, may be due not only to the beneficial effects of Si fertilization (such as growth promotion, lodging resistance, and biotic and abiotic stress resistance), but also to certain indirect effects such slight pH changes and the uptake of macro- and micronutrients contained in the Si-based fertilizers [16]. Early studies on the effect of Si on plant growth were inconclusive, but studies that are more recent indicate that Si can have a beneficial effect on many aspects of plant growth, most notably in rice. Tibbitts [17] reported the effect of supplemental silicon (Si) on wheat (*T. aestivum* cv. "USU-Apogee") from studies in a mini-lysimeter system imposing drought and salinity stress. There was no effect of Si on the harvest index, TGW or grains per spike.

Increased Si concentrations in plants not only maintain the water status but also improve drought resistance by regulating the leaf water potential, helping in CO_2 assimilation and decreasing transpiration through the adjustment of the leaf area [18]. A study by Ming et al. [19] suggests that Si application increases the water and osmotic potential in roots and leaves. Xu et al. [20] reported that Si-mediated changes result in a new balance of endogenous hormones and enhance the tolerance of the wheat plants to drought stress. Based on the results of previous studies, it can be concluded that foliar nutrition should be introduced as a standard treatment in the crop management of many species of agricultural plants. It can help farmers to increase crop yields [21].

Si should be used in organic crops where problems sometimes occur with plant nutrition and pest pressure, and only a limited range of fertilizers and plant protection products is permitted for use in organic farming. This limited range contributes to water stress that is especially hard for inadequately nourished plants to tolerate. In another paper was assessed how Si influenced the growth parameters and yield of spring wheat, both in powder and liquid form, applied to soil and leaves, respectively, and in combined methods of application. Si stimulated the growth of organic spring wheat and increased grain yields. Liquid Si was more effective than powdered Si, and the combined application of Si to soil and leaves was more effective than only soil or only foliar [22]. The research hypothesis of this work was based on the assumption that the reaction of wheat to the use of silicon may vary depending on the variety, also. Moreover, the work took into account an additional factor determining the effective use of silicon, concerning the varied water conditions in the course of wheat vegetation. Since the effectiveness of silicon application depends on the structure of silicon compounds and the way they are used, the question arises whether the usefulness of silicon may differ by genotype within a given crop species.

The potential of Si should be used in organic crops where there are problems with plant nutrition and pests due to the strict rules about the application of fertilizers and conservation measures in organic farming. In this growing system, water stress tolerance is particularly difficult for plants that are often less well fed. Therefore, an effective method of silicon delivery, including seed treatment, needs to be developed to minimize the harmful effects of abiotic and biotic stress factors. Chemical dressing is forbidden in organic farming; therefore, natural products are tested for this purpose [23,24].

The aim of the study was to determine the effect of powder and liquid silicon used as seed dressing and foliar treatments on the growth and quality and quantity of yield of three cultivars of wheat grown organically under various conditions of water availability in soil.

2. Materials and Methods

The field experiments under an organic regime were conducted in the years of 2018–2019 at an experimental agricultural station (52°2′ N; 17°4′ E) of the Institute of Plant Protection, National Research Institute (IPP-NRI), in Poland. The experiment was performed with Harenda, Rusałka and Serenada cultivars of *T. aestivum* L., which were grown in medium-heavy soil and followed potatoes in crop rotation. The three selected spring wheat cultivars were recommended in Poland to be grown in organic farming [25]. Soil samples were taken at the level of 0–20 cm (as a spade test), and the soil chemical properties of the experimental fields were analyzed. The average values of soil fertility from the two experimental years were as follows: the soil pH was slightly acidic (6.1), the organic matter content low (1.3%), P (112 mg kg^{-1}) and K (129 mg kg^{-1}) medium, and Mg (64 mg kg^{-1}) content high, which made the soil appropriate for growing spring wheat.

2.1. Summary of the Varieties Used in the Experiments

Rusałka—Qualitative variety (group A). Yield good or very good. Poor disease resistance. Medium TGW, high to very-high bulk density. High protein content, high amount of gluten. Large to very-high SDS sedimentation rate. The flour yield is quite low.

Serenade—Qualitative variety (group A). Good yield. Moderate disease resistance. TGW very high, bulk density high to very-high. High to very-high protein content, very high amount of gluten. Very high SDS sedimentation rate. Flour yield is average.

Harenda—Bread variety (group B). High disease resistance. Average TGW, high bulk density. Protein and gluten content are quite high. Very high SDS sedimentation rate. Average flour yield.

2.2. Meteorological Conditions during Tests

The meteorological conditions differed markedly in the growing seasons of 2018 and 2019. According to data from the Agricultural Meteorological Station of the Institute of Plant Protection, National Research Institute, located in Winna Góra, precipitation in the 2018 growing season was very similar to the average for the period of 1998–2017, but the temperature was higher by 2.5 °C (Table 1). The water available in the soil was assessed on the basis of both the precipitation/snowfall in the winter time until sowing time (November–April) and precipitation during the growing season in both experimental years (Table 1). In 2019, the rainfall for the growing season (April–August) dropped from 245.6 mm to 101.1 mm and was ca. 2.5-times lower than in 2018, causing high water stress. To sum up, the growing seasons of 2018 and 2019 had contrasting weather conditions characterized by a typical rainfall rate in 2018 and a very dry season in 2019 (Table 1). In the 2017/2018 winter–spring time, the total rainfall was 195.7 mm, and in the 2018/2019 season, a much lower snow/rain total of only 128.7 mm was recorded.

Table 1. Mean air temperatures and rainfall during spring wheat vegetation; data for the period 1998–2017 and for 2018 and 2019, Meteorological Station in Winna Góra.

Month/year	**Means for 1998–2017**		**2018**		**2019**	
	Temp., °C	**Rainfall, mm**	**Temp., °C**	**Rainfall, mm**	**Temp., °C**	**Rainfall, mm**
April	9.5	30.5	13.7	28.9	10.7	6.1
May	14.2	52.7	17.5	37.2	12.4	83.4
June	17.4	52.4	19.0	48.0	22.7	2.1
July	19.7	85.5	20.9	112.8	19.5	4.7
August	19.1	63.1	21.6	18.7	21.2	4.8
Mean/sum April–August	16.0	284.2	18.5	245.6	17.3	101.1

2.3. Field Experiment Design

Two silicon products were used—AdeSil® as a powder formulation and ZumSil® as a liquid trade formulation. ZumSil™ is a 24% solution of monosilicic acid. AdeSil® is amorphous diatomaceous earth with a flour texture and contains 89−95% amorphous silica (SiO_2). The studies concerned seed dressings carried out as a simple treatment or combined with three foliar treatments. Different combinations were used: (1) untreated plot, (2) only seed dressing, (3) three foliar treatments, and (4) seed dressing combined with three foliar treatments. For the seed dressing, a powdered form of silicon was used at a dose of 0.5 kg/100 kg of seed and then mixed with a liquid form of silicon at a dose of 0.5 L/100 kg of seed. The foliar treatments were performed with a liquid form of silicon at a dose of 0.5 L with 200 L of water per hectare. Three foliar applications were performed at the following stages of plant development: BBCH 23 (3 tillers detectable), BBCH 31 (first node) and BBCH 39 (flag leaf); the time of the intervals between the foliar sprays was 7–10 days. Each combination was used on plots of 24 m^2 and repeated three times. The experiment was carried out using the random plot system. Plots devoid of silicon application were used as the control. Wheat was sown on the 8th and 2nd of April of 2018 and 2019, respectively, with standard row spacing (12.5 cm), with a standard sowing ratio of 200 kg of grain per hectare. Due to the prohibition of synthetic herbicides in organic farming, only mechanical weed control was performed. No mineral fertilizers were used. Ten young plants were collected from each plot, and two growth parameters (the lengths of their leaves and roots) after the first foliar treatments (at the BBCH 29 stage—end of tillering) were measured manually using graph paper. After the harvest, the TGW and the yield were established. In 2018, spring wheat was harvested on 12 August, while in 2019, when there was a severe drought, harvest was performed on 29 July.

2.4. Laboratory Analysis Grain Quality Parameters

The quality of the harvested grain was evaluated using multifunctional equipment available in the laboratory. A qualitative analysis was performed using a FOSS Infratec™ 1241 Grain Analyzer (FOSS, Hilleroed, Denmark). For the analysis of crude protein density, wet gluten and bulk density, a cleaned and dry 0.5 kg grain sample was collected from each combination of experiments in 2018 and 2019. Each analyzed grain sample (0.5 kg) consisted of sub-samples taken from each plot in one combination. The device is calibrated and accredited once a year.

2.5. Statistical Analysis

The normality of the distribution of the observed traits was tested. Three-way (year, cultivar and method of silicon supply) analysis of variance (ANOVA) was performed to verify the hypotheses of the lack of effects of the year, cultivar and method of silicon supply as well as the interactions year × cultivar, year × method of silicon supply, cultivar × method of silicon supply and year × cultivar × method of silicon supply on the variability of the thousand-grain weight, yield, length of leaves per plant and length of roots per plant. The means values and standard deviations were calculated for all the observed traits. The significance of the differences between the mean values was verified with Tukey's test at a level of $p < 0.05$. The GenStat v. 18 statistical software package was used for all the analyses.

3. Results

The results of analysis of variance indicated that all four observed traits (the thousand-grain weight, yield, length of leaves per plant and length of roots per plant) were influenced by the cultivar, method of silicon application and water availability in the soil (Tables 3–6), as well as the interaction of year × cultivar × method of silicon supply being confirmed (Table 2).

Table 2. Mean squares (m.s.) from three-way analysis of variances for four observed traits: thousand-grain weight (TGW), yield, length of leaves per plant and length of roots per plant.

Source of Variation	Thousand-Grain Weight		Yield		Length of Leaves per Plant		Length of Roots per Plant	
	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.
Year	1	3701.2 ***	1	12.47 ***	1	7.427	1	7.001
Method	3	39.08 ***	3	2.84 ***	2	235.3 ***	2	24.87 **
Cultivar	2	115.75 ***	2	6.466 ***	3	26.09 ***	3	10.99 *
Year × Method	3	2.705 ***	3	0.013	2	24.14 **	2	2.618
Year × Cultivar	2	12.64 ***	2	0.198 ***	3	3.967	3	1.296
Method × Cultivar	6	1.800 ***	6	0.100 ***	6	159.7 ***	6	73.69 ***
Year × Method × Cultivar	6	1.008 ***	6	0.060 ***	6	13.4 **	6	7.157
Residual	36	0.031	36	0.005	372	3.631	372	4.076

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; d.f.—number of degrees of freedom.

The main effects of the year as well as the year × cultivar interaction were significant for the thousand-grain weight and yield (Table 2). The year × method of silicon supply interaction was statistically significant for the thousand-grain weight and length of leaves per plant; however, the year × cultivar × method of silicon supply interaction was significant for the thousand-grain weight, yield and length of leaves per plant (Table 2). The effect of Si application on the growth parameters of young wheat development, the grain yield and its quality was significant and related to water soil content; the results are presented in Table 3, Table 4, Table 5, and Table 6.

Table 3. Growth parameters of common wheat plants evaluated in the BBCH 29 growth stage depending on different methods of Si application.

		Si Application Method			
Cultivar	**Year**	**Untreated**	**Seed Dressing**	**Foliar Treatments**	**Seed and Foliar Treatments**
		Mean length of leaves per plant, cm			
Harenda	2018	20.60 ± 0.34 ^{a}	21.05 ± 0.12 ^{a}	20.00 ± 0.32 ^{a}	20.40 ± 0.09 ^{a}
	2019	21.88 ± 0.06 ^{a}	19.94 ± 0.26 ^{b}	18.92 ± 0.63 ^{bc}	17.73 ± 0.42 ^{c}
Rusałka	2018	20.36 ± 0.21 ^{a}	20.93 ± 0.11 ^{a}	20.24 ± 0.08 ^{a}	20.81 ± 0.23 ^{a}
	2019	15.25 ± 0.50 ^{b}	20.20 ± 0.78 a	19.57 ± 0.38 ^{a}	20.49 ± 0.62 ^{a}
Serenada	2018	20.75 ± 0.11 ^{a}	20.68 ± 0.32 ^{a}	20.27 ± 0.21 ^{a}	20.44 ± 0.15 ^{a}
	2019	19.26 ± 0.21 ^{b}	23.79 ± 1.04 ^{a}	23.24 ± 0.42 ^{a}	21.55 ± 1.07 ^{a}
		Mean length of roots per plant, cm			
Harenda	2018	13.03 ± 0.10 ^{a}	12.96 ± 0.21 ^{a}	12.82 ± 0.09 ^{a}	12.84 ± 0.51 ^{a}
	2019	14.44 ± 0.21 ^{a}	12.41 ± 0.43 ^{b}	11.89 ± 0.69 ^{b}	10.19 ± 0.22 ^{c}
Rusałka	2018	12.89 ± 0.34 ^{a}	12.43 ± 0.56 ^{a}	12.84 ± 0.23 ^{a}	12.68 ± 0.19 ^{a}
	2019	11.02 ± 0.72 ^{c}	12.51 ± 1.04 ^{bc}	14.15 ± 0.41 ^{a}	13.55 ± 0.45 ^{ab}
Serenada	2018	13.98 ± 0.05 ^{a}	13.85 ± 0.14 ^{a}	13.73 ± 0.45 ^{a}	14.01 ± 0.28 ^{a}
	2019	11.74 ± 1.05 ^{b}	13.29 ± 0.81 ^{a}	13.56 ± 0.22 ^{a}	13.76 ± 0.37 ^{a}

Values followed by the same letter are not statistically different at $p < 0.05$.

Table 4. Thousand-grain weight (TGW) (g) of wheat in relation to method of Si application and wheat cultivar.

		Si Application Method			
Cultivar	**Year**	**Untreated**	**Seed Dressing**	**Foliar Treatments**	**Seed and Foliar Treatments**
Harenda	2018	26.32 ± 0.22 ^{c}	29.01 ± 0.31 ^{b}	28.78 ± 0.32 ^{b}	31.38 ± 0.50 ^{a}
	2019	26.48 ± 0.77 ^{c}	27.85 ± 0.70 ^{b}	26.62 ± 0.48 ^{b}	29.37 ± 0.47 ^{a}
Rusałka	2018	30.09 ± 0.85 ^{a}	32.09 ± 0.50 ^{a}	30.34 ± 0.57 ^{a}	33.00 ± 0.27 ^{a}
	2019	28.85 ± 0.82 ^{a}	29.05 ± 0.11 ^{a}	28.98 ± 0.86 ^{a}	29.80 ± 0.30 ^{a}
Serenada	20182019	31.89 ± 0.41 ^{b}	32.09 ± 0.78 ^{a}	32.02 ± 0.23 ^{a}	33.03 ± 0.51 ^{a}
		30.80 ± 0.48 ^{a}	30.20 ± 0.64^{ca}	30.67 ± 0.59 ^{a}	31.18 ± 0.15 ^{a}

Values followed by the same letter are not statistically different at $p < 0.05$.

Table 5. Yield (t) in relation to method of Si application and wheat cultivar.

Cultivar	**Year**	**Si Application Method**			
		Untreated	**Seed Dressing**	**Foliar Treatments**	**Seed and Foliar Treatments**
Harenda	2018	2.92 ± 0.18 ^{b}	3.62 ± 0.26 ^{a}	3.23 ± 0.20 ^{a}	3.94 ± 0.19 ^{a}
	2019	1.66 ± 0.16 ^{c}	2.48 ± 0.24 ^{b}	2.04 ± 0.03 ^{bc}	2.87 ± 0.12 ^{a}
Rusałka	2018	3.60 ± 0.28 ^{b}	3.93 ± 0.19 ^{b}	3.78 ± 0.21 ^{b}	4.98 ± 0.33 ^{a}
	2019	2.89 ± 0.05 ^{c}	3.28 ± 0.13 ^{b}	3.09 ± 0.07 ^{bc}	3.74 ± 0.18 ^{a}
Serenada	2018	4.06 ± 0.32 ^{b}	4.47 ± 0.34 ^{ab}	4.32 ± 0.07 ^{b}	4.71 ± 0.19 ^{a}
	2019	3.12 ± 0.13 ^{c}	3.74 ± 0.06 ^{ab}	3.33 ± 0.18 ^{bc}	4.10 ± 0.22 ^{a}

Values followed by the same letter are not statistically different at $p < 0.05$.

Table 6. Selected parameters of wheat grain quality in relation to Si application method and wheat cultivar.

Cultivar	**Year**	**Si Application Method**			
		Untreated	**Seed Dressing**	**Foliar Treatments**	**Seed and Foliar Treatments**
		Crude Protein (%)			
Harenda	2018	13.7 ± 0.43 ^{a}	14.1 ± 0.36 ^{a}	13.9 ± 0.36 ^{a}	14.4 ± 0.51 ^{a}
	2019	14.3 ± 0.14 ^{b}	15.9 ± 0.34 ^{a}	14.8 ± 0.37 ^{b}	16.5 ± 0.41 ^{a}
Rusałka	2018	13.7 ± 0.35 ^{a}	14.0 ± 0.22 ^{a}	13.8 ± 0.10 ^{a}	14.2 ± 0.11 ^{a}
	2019	14.5 ± 0.26 ^{a}	14.9 ± 0.18 ^{a}	14.6 ± 0.14 ^{a}	15.0 ± 0.19 ^{a}
Serenada	2018	13.2 ± 0.27 ^{a}	13.5 ± 0.46 ^{a}	13.4 ± 0.42 ^{a}	13.7 ± 0.11 ^{a}
	2019	13.9 ± 0.15 ^{a}	14.5 ± 0.37 ^{a}	14.4 ± 0.41 ^{a}	14.6 ± 0.14 ^{a}
		Wet Gluten (cm^{3})			
Harenda	2018	30.1 ± 0.76 ^{a}	31.8 ± 0.76 ^{a}	30.9 ± 0.45 ^{a}	32.1 ± 0.98 ^{a}
	2019	31.4 ± 0.98 ^{b}	34.9 ± 0.87 ^{a}	32.7 ± 0.98 ^{b}	36.0 ± 1.80 ^{a}
Rusałka	2018	29.4 ± 0.41 ^{a}	30.1 ± 0.98 ^{a}	29.7 ± 0.87 ^{a}	30.2 ± 0.65 ^{a}
	2019	32.2 ± 0.43 ^{a}	32.6 ± 0.78 ^{a}	32.6 ± 0.76 ^{a}	33.9 ± 0.65 ^{a}
Serenada	2018	33.7 ± 0.56 ^{a}	34.8 ± 0.54 ^{a}	34.2 ± 0.62 ^{a}	35.5 ± 0.78 ^{a}
	2019	38.2 ± 0.71 ^{a}	40.2 ± 0.91 ^{a}	39.4 ± 0.75 ^{a}	40.4 ± 0.86 ^{a}

For each parameter of wheat grain quality, values followed by the same letter are not statistically different at $p < 0.05$.

3.1. Growth Parameters

In 2018, when no problems with the availability of soil water for plants were observed, no differences in the development of the leaves and roots of young wheat plants were noticed (Table 3). The measurements were made after the first Si foliar application. Neither the wheat cultivar nor the Si form and method of application influenced the wheat.

In 2019, a dramatic water shortage changed the growth pattern of young wheat plants. The rainfall in April was five-times lower than usual (Table 1), but sufficient rain in May saved the plants from wilting. The wheat cultivars showed a different pattern of reaction to these spring water conditions. Cultivar Harenda developed the longest leaves without Si. Seed treatment significantly reduced leaf development. Treatment with foliar Si made the situation worse, and the combination of seed and foliar Si produced the worst results (Table 3). The same pattern of reaction to Si application was noted in the root development of this cultivar. Contrasting results were noted in 2019 in the development of young wheat plants of the Rusałka and Serenda cultivars. The mean length of Rusałka leaves was the shortest on the control object, and the leaves were shorter by ca. 25% than the leaves of the plants treated with Si, regardless of the form and the method of application (Table 3). The Rusałka roots were also the shortest in the control plots; however, the differences were not statistically significant compared to plants developed from seed dressing. This cultivar developed longer roots in response to Si seed dressing and foliar application, and the longest when only foliar applications were used. The Serenada cultivar showed almost the same pattern of development as Rusałka. It had the shortest leaves and roots when no Si treatment was applied; however, the length of the leaves and roots increased to the same degree as those of Rusałka, regardless of the form and method of Si application.

3.2. Impact of Si on Grain and Yield Development

The thousand-grain weight (TGW) is significantly affected by water stress and wheat cultivar [26]. A water deficit can affect plant growth and development in all stages; in early stages, the rate of tiller appearance, leaf appearance and leaf area are reduced; later on, the length of the stems is reduced together with the number of grains per spike, and stress after anthesis shortens the duration of grain filling, thus reducing the grain size [27]. In the presented results, the wheat cultivar also had a marked impact on the grain parameter, with the lowest TGW noted in the Harenda cultivar not treated with Si. This effect was found in both 2018 and 2019, and the TGWs stood at 26.32 and 26.48 g, respectively (Table 4).

The reduction of the grain weight as a basic parameter resulted in a very low wheat yield in the control plots, as the plant density (data not shown) was the same in all combinations of the study. The Si treatment had a positive effect on grain development, and the highest values of TGW were associated with the combined (seed and foliar) Si treatment. The larger grain size of the cultivar Rusałka was more frequent than in the cultivar Harenda, but in this case, no statistical effect of Si treatment on the TGW was observed. The grain development of the Serenada variety was similar to that of the Rusałka cutivar, although in 2018, the Serenada grains harvested from untreated plots were smaller than in the other combinations (Table 4).

In 2018, the weather during the growing season was typical, especially for rainfall; the average grain yield of the three spring wheat cultivars was almost four tons per hectare (3.90 t per hectare). In 2019, which was very dry, the average yields of wheat dropped by almost 1 t per hectare (to 3.03 t per hectare), that is, by ca. 25%. The cultivar choice, also an important factor, influenced the grain yields; the highest grain yields were obtained from the Serenada cultivar (3.98 t per hectare), somewhat lower yields were obtained from the Rusałka cultivar (3.66), and the lowest were from the Harenda cultivar (2.85 t per hectare) (data not shown).

The strongest response to Si treatment was found in the Harenda cultivar, both in normal 2018 and dry 2019 (Table 5). In both years, the lowest yields were harvested from the control plots. In 2018, the difference in grain yield between the control and foliar-treated wheat was 10%, and in dry 2019, it was 19%. The yield of wheat harvested in the control plots in 2019 was only 1.66 t per hectare, which is probably not profitable for organic-wheat growers. In the same year, the yields from the control plots of the Rusałka and Serenada cultivars were 2.89 and 3.12 t per hectare, respectively. Thus, the yield of the Serenada cultivar was almost double that of the Harenda cultivar. The most efficient way of Si application was the combined seed and foliar treatment, which resulted in a yield increase of the Harenda cultivar by 26% in 2018 and 42% in 2019. Although the increases in yields were high in both years, the result obtained in dry 2019 was exceptionally high.

The most effective method of Si application was the combined treatment of seed dressing and three sprayings. This application method increased the grain yields of the Rusałka cultivar by 28% in 2018 and 23% in 2019. In the case of the Serenada variety, the increase in yields was particularly noticeable in 2018 (18.8%), when no water-limiting drought was recorded, and much higher in dry 2019, when the yield increased by 24%.

3.3. Grain Quality

A few differences in the grain quality parameters in relation to Si application and cultivar choice were noted. In the case of the Rusałka and Serenada wheat cultivars, Si application had a statistically insignificant effect on the protein content in grain, but a tendency to promote protein accumulation in the grain of the Rusałka cultivar when the wheat was treated with Si as a seed dressing and foliar spraying was noted (Table 6). In 2019, for the Harenda cultivar, a higher protein content was the result of Si seed dressing (15.9%) and the combined Si treatment (seed dressing and three foliar sprayings) (16.5%). A lower protein content was found in the smallest grains from the control plots (14.3%) and foliar treatments (14.8%).

Gluten, another basic parameter of wheat grain quality, usually correlates with protein content. In general, the gluten content was high, showing a high baking quality for the grain. In a comparison of the results from 2018 and 2019 (normal and dry growing seasons), a tendency towards higher gluten content was found in the latter year. The Harenda cultivar grain harvested in 2018 had no difference in quality; in the dry 2019, the highest gluten content was in grain harvested from the plants treated with Si, seed dressing and combined application methods; the lowest content of gluten was noted for untreated crops (Table 6). The gluten contents of the Rusałka and Serenada cultivars were the same in all combinations, although Serenada showed a tendency towards greater gluten accumulation as a result of the combined seed dressing and foliar Si treatments. Another basic parameter used to assess the baking quality of the wheat grain was its bulk density, and a minimum value of 73 kg per hectoliter is expected for the best quality grain. This value was not always met in our research (Figure 1). This was the case with the Harenda variety in all experimental variants during the 2019 dry season, so this variety not only produced lower yields but also, in some respects, lower quality.

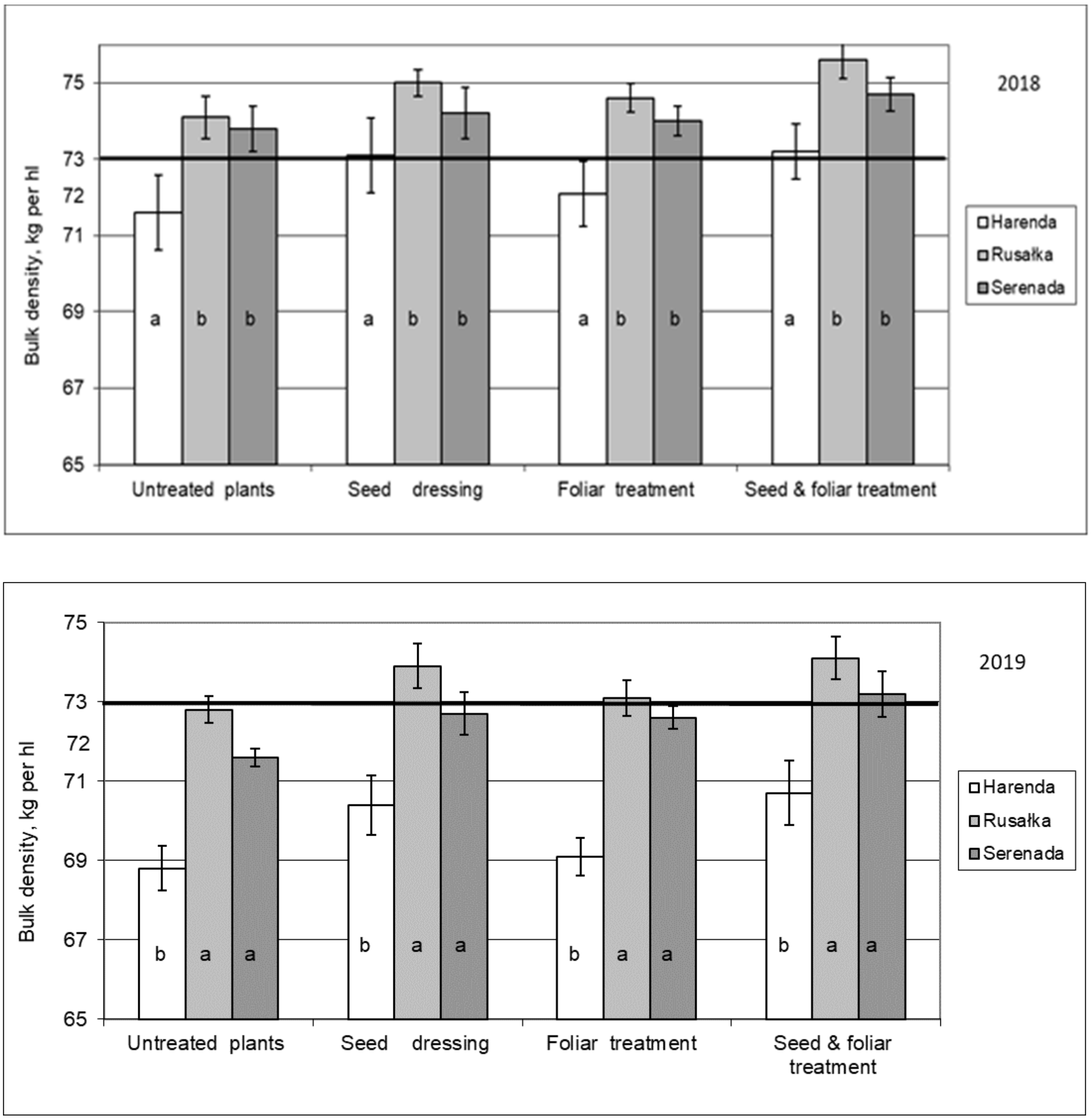

Figure 1. Effect of Si application method on bulk density of wheat cultivars in 2018 and 2019. Values followed by the same letter are not statistically different at $p < 0.05$. The bold line indicates the bulk density guide value (73 kg per hL) for wheat grain.

4. Discussion

In our research, it was shown that the use of silicon had a positive effect on the development and yielding of wheat grown organically, and the scale of this effect depended on both rainfall deficiencies and the variety. There are limited studies available in the literature on the effectiveness of Si in wheat, especially in organic farming and under drought stress. Ahmad et al. [28] investigated the role of silicon in the fertilization of wheat (*T. aestivum*) under various soil moisture conditions and found that Si application significantly improved plant biomass, growth and spike weight. This statement is in line with our observations. The use of monosilicic acid—as in the presented paper—absorbed by plants in almost every crop (compared to the control) resulted in an increase in the root mass, the development of thicker shoots, a larger leaf area and a higher chlorophyll content. Thus, the use of Si may have an indirect effect on the improvement of plant growth parameters by increasing the mass of roots and is associated with a higher uptake of nutrients (PCa, K, Si and Bo) from the soil [29]. The synergistic effects of silicon (Si) and salicylic acid (SA) applied at 6 mM Si, 1 mM SA and 6 mM Si + 1 mM SA on the grain yield and some key physiological characteristics of the wheat cultivars Shiraz (drought-sensitive) and Sirvan (drought-tolerant) were investigated [30]. Water-stress alleviation and yield improvement in the wheat cultivars by Si and SA application were attributed partly to improved osmotic adjustment and antioxidant activity, as well as to a more favourable water status under stress conditions. Generally, it was concluded that Si and SA application proved to have a great potential in advancing the grain yield of wheat in drought-prone areas [30]. This statement is confirmed by our results and can be a recommendation for farmers fighting with growing problems with water limitation during the growing season. The studies conducted by Guevel et al. [31] also confirm the beneficial effect of silicon application on wheat plants; however, effect Si amendment, either through the roots or the leaves had a biostimulating effect and did not increase plant growth. Their results lead to the conclusion that Si is primarily, if not exclusively, absorbed by the root system and that such absorption by the roots is necessary for an optimal prophylactic effect against powdery mildew. Although less effective than root applications, foliar treatments with both Si and nutrient salt solutions led to a significant reduction in powdery mildew on wheat plants. This suggests a direct effect of the products on powdery mildew rather than one mediated by the plant as in the case of root amendments. In our experiments were also made observations on the healthiness of the plants, and the frequency of spike diseases caused by *Septoria nodorum* and Fusarium spp. were noted. The severity of these diseases varied depending on the variety and use of silicon—this issue will be discussed in the next manuscript. The foliar application of silicon has a biostimulative effect, and the best results are observed in conditions stressful for plants such as salinity, a deficiency or excess of water, high and low temperatures, and the pressure of diseases and pests, etc. [21].

The plant response to Si application is greatly influenced by the genotype, and this phenomenon was noted by Dufey et al. [32] in rice crops. Our study also confirmed the impact of the genotype of wheat on the efficacy of silicon, similar to other studies [30]. The yielding of wheat depends on the wheat cultivar and conditions of growing. We grew the Harenda, Rusałka and Serenada cultivars, as they are recommended for organic farming by the Institute of Soil Science and Plant Cultivation for organic farming [27]. In that study, yields of 5.58, 4.90 and 4.89 t per hectare were obtained for the Harenda, Serenada and Rusałka cultivars, respectively [33]. In our research, the yields of these cultivars were much lower and were 3.98, 3.66 and 2.85 t per hectare for the Serenada, Rusałka and Harenda cultivars, respectively. Our field studies were carried out in the region of Wielkopolska, the Polish region with the greatest rainfall shortages, so the yields are much lower than in the other regions of Poland. Among the cultivars grown, Harenda gave the lowest yields, indicating that it did not adapt to such environmental pressure. At the same time, Harenda reacted the best to Si application, especially in the growing season of dry 2019. Dufey et al. [32] stated that the choice of stronger Si-accumulating varieties could be valuable in the improvement of wheat resistance to drought stress. The same cultivars grown in a conventional farming system showed almost no difference in yield, and, according to data from the Research Centre for Cultivar Testing in Poland (COBORU), the three wheat cultivars yielded 10.3, 10.0 and 9.8 t per hectare, respectively, in 2018 [34]. This proves that the genotype of the wheat cultivars was a factor determining the development and yielding of the plants depending on the agricultural cultivation system. In this way, treatments with silicon can minimize the negative impact of a stress factor, e.g., a lack of water, especially in organic farming.

The most effective method of silicon application was the combined method, which increased the wheat yield by ca. 25% in both study years (normal and dry), but in the case of the Harenda cultivar, during the dry year, the yields almost doubled, increasing by 42%. The combined Si application produced the best results; the yield response to Si may be related to an improved uptake of this element and the methods of delivery to plants, and it was confirmed for sugarcanes [35]. Guevel et al. [31] also concluded that the combined foliar and soil application was the most effective for wheat health. Segalin et al. [36] revealed that the foliar application of silicon affected neither the yield nor quality of the wheat grain of different cultivars. Walsh et al. [16] also could not confirm any beneficial effects on the plant growth, grain yield and grain protein of irrigated winter wheat grown in non-stressed conditions; a Si product (sourced from a high-energy amorphous, non-crystalized volcanic tuff) was applied twice at rates of 140, 280 and 560 kg Si ha^{-1}, once at planting and once at tilling time. Korunic et al. [37] evaluated the effect of diatomaceous earth (DE) on grain quality and noted that it reduced the bulk density of durum wheat. In our observation, this fact was not confirmed; lower values of bulk density were noted only in 2019 (dry year) compared to 2018 (Figure 1). The grain quality depends not only on the cultivar but also on the management system (organic vs. conventional). Spring wheat cultivars grown under organic and conventional management systems were found to have different quality yield parameters (bread-making) and phospholipid fatty acid (PLFA) profiles. In the organic system, the wheat yields were roughly half of the conventional yields, but the protein content was higher in the organic system. In general, high protein and gluten contents were obtained in our study, although this is not in agreement with findings by Nelson et al. [38], in which research from different parts of the world reported lower quality parameters (contents of protein and gluten, the TGW and the sedimentation index described by Zeleny) of wheat grown under an organic farming regime [39–42]. In our study, the bulk density of the Harenda cultivar in the control plots in 2018 and all the study variants in the dry year of 2019 did not meet the EU standards for bread-making wheat [43]. Moreover, our results show no influence of silicon on the protein and gluten contents, with the exception of for the Harenda cultivar in the dry 2019, when all the quality parameters (protein and gluten contents and bulk density) were the lowest in the control area. In the case of the Harenda cultivar, a positive effect of Si application on the TGW was also found.

5. Conclusions

The increasing incidences of different biotic and abiotic stresses, especially drought, throughout the world have restrained the growth of wheat. Si application has a positive effect on wheat yields, and the scale of the effect depends on the application method, the wheat cultivar and the severity of the different water conditions in the soil. The Harenda cultivar was more prone to less soil water content than the Rusałka and Serenada cultivars. Under severe water stress, young Harenda plants slowed down their development after Si application but eventually increased their grain yield to a greater degree than in the case of the other two cultivars. Silicon increased the yields of the three wheat cultivars, and the highest yields were harvested in the plots with combined silicon treatments. The values of the thousand-grain weight, yield, length of leaves per plant and length of roots per plant were statistically significantly determined by the cultivar and method of silicon supply as well as the interaction of the cultivar × method of silicon supply. Confirming the interaction leads to the conclusion that the effectiveness of using silicon may vary depending on the wheat variety. The value of the presented research is the confirmation of the possibility of mitigating plant stress due to limited water availability in the soil, especially in the case of cultivars sensitive to this stress factor. An extremely important conclusion is also demonstrating the effectiveness of the methods of silicon application, with an indication of the combined method of silicon application and the seed dressing method dedicated especially to organic farming.

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