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Study of the effects of silicon and sulphur foliar fertilisation on yield components and yield in different winter oat cultivars

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SUMMARY

The aim of this work was to study the effect of sulphur and silicon foliar fertilisation treatment in different Hungarian-bred winter oat cultivars on the yield and the yield components, e.g. panicle ear^{-1} numbers per square meters, number of panicle nodes, number of spikelets per panicle, and thousand kernel weight (TKW) in the 2022–2023 growing season. The obtained results show that the applied fertilisers influenced the measured parameters, and we get the highest yield at the combined treatment – where silicon and sulphur was both applied –, and unexpectedly the lowest when only silicon was applied during the growing period. We measured the highest number of panicles m^{-2} at the sulphur treated experimental plots, and the lowest at the silicon treatment. We measured the average number of nodes of the panicle, and we can say that the sulphur fertilisation caused significantly higher values than any other treatment. Talking about the spikelet numbers, we get the highest value at the sulphur fertilisation, and the lowest at the control plots. However, our result wasn't that prominent in the case of TKW, we get the highest weight at the silicon treatment, and the lowest at the sulphur fertilisation.

Keywords: *winter oats; productivity; foliar fertilization; yield components*

INTRODUCTION

Oat *(Avena sativa* L.) is a very important crop, not to mention it's role in human food and animal feed (Daou and Zhang, 2012). This plant is stands out among other grains due to its nutritional content and high content of special fiber (ß-glucan) (Paudel et al., 2021). The main difference between winter and spring oats is that winter oats have a longer growing season and higher yield. Additionally, they can be harvested earlier under local climatic conditions, thus avoiding the summer drought period more effectively (Stanton, 1953).

The increasing deficiency of sulphur in soils has become a major concern, primarily due to changes in agricultural practices and reduced atmospheric concentrations. Additionally, plants' sulphur requirements have somewhat increased (Lucheta and Lambais, 2012). Sulphur contributes to more efficient nitrogen utilisation, and its positive effects are particularly pronounced when nitrogen is not a limiting factor (Salvagiotti and Miralles, 2008). Consequently, sulphur indirectly contributes to achieving higher yields. The application of sulphur in foliar form is not a new practice; Waraich et al. (2020) studied its effects on rapeseed and found that it increased yield and positively affected yield components (number of silique per plant, seeds per siliques, Thousand Seed Weight) under heat stress conditions. Orlovius (2001) tested the effects of sulphur foliar fertilisation on several crops, including spring wheat. The results showed that applying sulphur-containing foliar fertilisers effectively and rapidly corrected potential nutrient deficiencies, leading to a significant increase in yield. According to Ali and his colleagues (2012), sulphur statistically significantly positively influenced wheat yield, the number of spikes, and TKW. In an experiment conducted by Khalifa and his colleagues (2016), the combined application of silicon and sulphur also significantly increased yield in maize.

The importance of silicon as a micronutrient has long been a debated question among researchers, and until the 1980s, it was not considered even under hydroponic conditions (Debona et al., 2017). However, the situation has changed considerably since then. Monocots, such as oats, are typically high accumulators of silicon (Richmond and Sussman, 2003; Thakral et al., 2021). Although silicon is considered a "non-essential" nutrient, its yield-enhancing effect has been demonstrated in several studies and acknowledged (Korndörfer and Lepsch, 2001; Kutasy et al., 2023; Kutasy et al., 2022), with several publications referring to it as a quasi-essential nutrient (Rodrigues et al., 2015; Datnoff and Rodrigues, 2015). Its positive effects from a plant protection perspective are also recognized. For example, Laing and his colleagues (2006) noted that silicon application effectively increases plants' resistance to insects and diseases. The emergence of resistance is based on passive methodology, involving the formation of a kind of mechanical barrier, but it appears that silicon also actively participates in defense mechanisms. Aouz and his colleagues (2023) investigated the effect of externally applied silicon on wheat and found that it significantly increased the plants' resistance to heat and salt stress. It is certain that several publications refer to the successful effect of silicon against biotic and abiotic stresses.

The preceding lines illustrate why we are curious about the effects of silicon and sulphur. Our basic assumption was that both Si and S are expected to have a positive impact on yield and yield productivity elements. The crop productivity elements plays a crucial role in determining yield formation at various

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phenological stages. So it is important to know what proportion of each element contributes to the yield.

MATERIALS AND METHODS

Experiment setting conditions

The field experiments have been set for the period of 2022–2023 in Hungary, at the Experimental Garden of the Campus of Böszörményi Street 138., which belongs to the University of Debrecen. The plots, where the experiment was set has a chernozem soil with great humus content.

Climate conditions

The climatic conditions during the growing season were favorable for cereals. In the autumn period of 2022, abundant rainfall occurred, forming sufficient reserves in the soil. Nothing proves this better than the fact that the amount of precipitation in September and December exceeded twice the respective monthly averages of precipitation over several years, as we can see it in *Table 1*. As a result, the sowing date had to be postponed, but thanks to the mild winter temperatures, the oats could enter the winter in an appropriate phenological phase, providing excellent conditions for overwintering due to the mild temperatures (January was slightly more than 6 °C warmer than the multi-year average temperature, but both December and January were warmer, approximately 2 °C higher). The winter period was followed by a prolonged spring period with average precipitation conditions, which had a positive impact on the development of oat plants. The dry period set in from June and peaked in July–August.

Table 1. **Local climatic conditions (Debrecen, 2022–2023)**

Mounths	Precipitation			Temperature		
	Multi-year monthly average precipitation (mm)	Monthly precipitation (mm) (2022–2023)	Deviation from the multi-year average (mm)	Multi-year monthly average mean temperature (ºC)	Monthly mean temperature (ºC) (2022–2023)	Deviation from the multi-year average (ºC)
September	48.5	161.0	112.5	15.8	15.8	0.0
October	41.0	7.6	-33.4	10.1	12.2	2.1
November	39.7	58.5	18.8	4	6.8	2.8
December	43.2	95.2	52.0	0.1	2.6	2.5
January	29.2	53.6	24.4	-1.6	4.4	6.0
February	35.2	14.9	-20.3	0.3	2.3	2.0
March	30.5	46.4	15.9	5.2	7.5	2.3
April	44.0	48.5	4.5	10.6	10.0	-0.6
May	54.3	77.4	23.1	16.2	17.1	0.9
June	64.6	122.5	57.9	18.8	20.3	1.5
July	68.7	35.9	-32.8	20.7	23.5	2.8
August	49.7	75.5	25.8	20.2	23.2	3.0

Source: Data from the measurement programme of the DE-MÉK PNK Agrometeorological Observatory and HungaroMet

Experimental design

The experiment was set up under small plot (4x3 m) conditions, with three independent repetitions. The oat was sown in 20 October 2022 with the dosage of 180 kg seed ha^{-1}. The forecrop was soybean, and we added 88.6 kg ha^{-1} N fertilisation (Urea, Nitrogen content: 46%) in the spring period. The seed was coated with tebuconazole, and we had weed control once, and pest control three times during the growing season. The harvesting occured on 28. July 2023. We took samples from each plot for further testing.

The applied 4 treatments:

- Control: added only 10 l water, no foliar fertilisation
- Si: using Optisyl (200g SiO_2 l^{-1}) with the dosage of 0,5 l ha^{-1}
- S: using Jello Fluid (1000g SO_3 l^{-1}) with the dosage of 5 l ha^{-1}
- Si+S: we applied both Optisyl and Jello Fluid with the same dosage of Si and S treatments

At 4 different date and phenological stages:

1. treatment: 2022. 11. 16. BBCH 13 (3 leaf stage)
2. treatment: 2023. 04. 18. BBCH 29 (end of tillering)
3. treatment: 2023. 05. 22. BBCH 52-57 (20%–70% inflorescence emerged)
4. treatment: 2023. 06. 03. BBCH 71-73 (milk rape stage)

We tested 6 locally-bred winter oat cultivar: GK Arany, Mv Hópehely, Mv Imperiál, Mv Kincsem, Mv Istráng and Mv Hóka.

Measurements

A yield and thousand kernel weight (TKW) were determined after harvest. We recorded the yield results of the respective plots, then determined the moisture content from some of the samples using drying cabinet. Subsequently, we calculated the dry weight of the respective plots, which was projected per hectare. To determine the TKW, we counted two hundred grains from harvested plot samples, then calculated the thousand kernel weight of the respective plots using the known moisture percentage. The yield of each sample was reduced to the standard humidity (14%). The yield productivity elements were determined on the crop prior to harvest but at full maturity on June 4., 2023.

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The number of panicles per square meter was counted using a special frame, which size was 0.5 m x 0.5 m. After that, five panicle were selected and separated per plot, and the number of panicle nodes and spikelets was determined on these.

Statistics

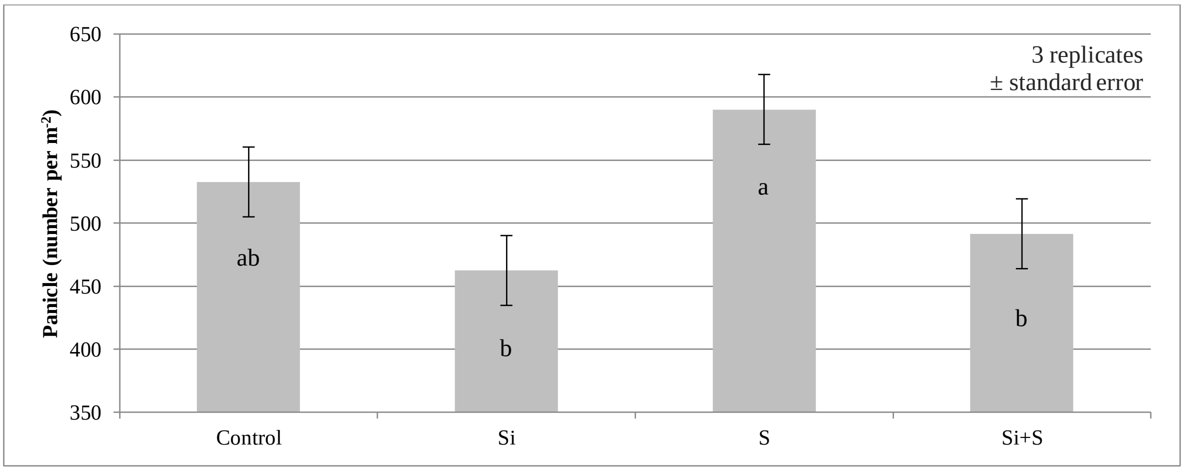
We analyzed the datas with a software called: IBM SPSS Statistics 22.0. We used the univariate general linear model to compare the means of the examined parameters. the results based on the one-way ANOVA tests. We used LSD post-hoc test for pairwise comparisons of the means. The alpha (significance level) was p=0.05. At the end we analyzed the correlation between the parameters with the 2-tailed Pearson's correlation analysis. The significance and the standard errors was showed on the diagrams and the tables.

RESULTS AND DISCUSSION

Number of panicles per square meter

Regarding the number of spikes per square meter, it can be stated that the highest value was measured in the plots treated with sulphur (S), averaging 590 spikes. This was followed by the control plots with 533 spikes. In the row, the next were the plots receiving the combined treatment (Si+S), with a total of 492 spikes, and finally, the plots treated with silicon (Si) had 462 spikes. It can be said that there is a noteable difference between the results of the S (590) and Si (462) treatments, which by number was 128 spikes. This difference is quite relevant because mathematically, assuming an average spikelet number of – for example – 52 spikelets per panicle, it would mean 6656 spikelets in total. Considering a thousand kernel weight (TKW) of 34 g, this would mean extra yield of 226 g per square meter, which, when calculated per hectare, would mean an additional theoretical yield of 2.26 tons! The results are shown in *Figure 1.* In Al and Mahmoud's experiment (2021) in oat, they observed a slight increase in the number of panicles m^{-2}, as an effect of sulphur treatment (an average of 382.6 panicles, which was 10 panicles more than the untreated plants results), similar to our experiment. Furthermore, In Artyszak publication (2018), we can read that silicon application also increased the number of panicles m^{-2} of wheat plants.

Figure 1. **Panicle count per square meter averaged over treatments (Debrecen, 2023)**



Note: The different letters mean significantly different values at p = 0.05 level

Number of nodes per panicle

As for the number of nodes per panicle, it can be observed that the sulphur (S) treatment resulted in a significantly higher number of spikelets compared to the other treatments, averaging 5.02 nodes. This was followed by the combined (Si + S) and silicon (Si) treatments with average values of 4.83 and 4.81, respectively. The lowest data was measured in the control plots, with a value of 4.68. These numbers are average values. Overall, it can be said that out of the 360 samples examined (5 spikes per plot, a total of 72 plots), in no case did we count less than 3 or more than 7 nodes On average, the most spikelets were counted on the first three nodes of the panicle, with the second node standing out, which is characteristic of the oat's panicle habitus. Interestingly, it is worth mentioning that we only counted 7 node in a total of 3 cases, which were associated with the GK Arany variety and the silicon treatment in one case, and with the Mv Istráng variety and the combined treatment in two cases. The above-mentioned data can also be read from *Table 2.*

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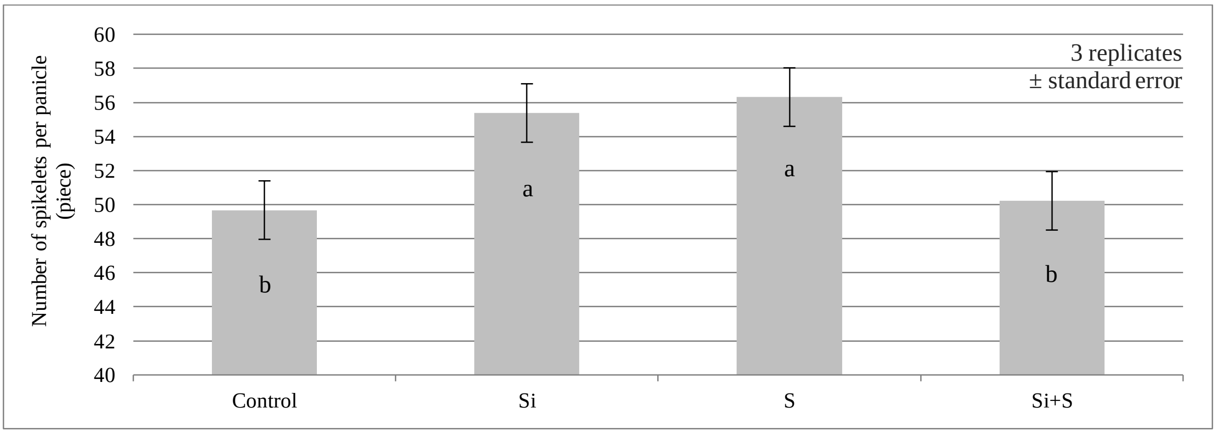
Table 2. **Overview of the datas of the number of spikelets on each node in panicles (Debrecen, 2023)**

Number of node	Mean of spikelets	Median of spikelets	N (spikelets)	Std. Deviation (spikelets)	Minimum (spikelets)	Maximum (spikelets)
1	11.70	10.00	360	7.579	0	43
2	13.36	12.00	360	6.168	0	34
3	11.46	11.00	360	4.069	2	24
4	9.37	9.00	353	3.092	3	27
5	8.62	8.00	241	2.687	3	17
6	7.81	8.00	64	2.309	2	13
7	4.00	3.00	3	1.732	3	6

Number of spikelets per plants

Regarding the number of spikelets, the results of plots treated with sulphur (S) and silicon (Si) significantly differed from those treated with the combined (Si+S) fertilisation and the control treatments itself. The highest average number of spikelets was measured under the sulphur treatment, with a value of 56.31 pc (piece). This was followed by the silicon treatment, which resulted in an average of 55.38 spikes per spikelet. With a larger scale jump, the plots receiving the combined treatment followed with a value of 50.22 pc, and finally, the control plots closed the list with 49.68 pc (*Figure 2)*. This means that the sulphur fertilisation caused 13% higher spikelets number compared to the control plots, and 11% higher spikelets number when the silicon treatment was applied. It's an interesting thing by the way, that when the combined treatment was applied, we only get 1% better results compared to the control plots, and the difference was not statistically significant. Comparing our results with other researchers's, it can be said that in several cases an increase in the number of spikelets was observed in response to silicon, even if the results were not statistically significant in oat and wheat crops (Soratto et al, 2012; Artyszak, 2018; Hassan and Alsulaiman, 2023). However, no significant changes in this parameter were observed in response to applied sulphur (Al and Mahmoud, 2021; Hussain and Leitch, 2008).

Figure 2. **Number of spikelets per plant averaged over treatments (Debrecen, 2023)**



Note: The different letters mean significantly different values at p = 0.05 level

Thousand kernel weight (TKW)

Regarding the thousand kernel weight, although there were no substantial differences, the highest values were measured in the plots treated with silicon (Si), with the value of 35.29 grams. This was followed by the control plots, with a value of 34.39 grams, and then the plots receiving the combined treatment with 33.93 grams. The sulphur-treated plots closed the list with TKW values of 33.28 gram. According to the statistical results, there was a significant difference only between the values of the Si and S treated plots. numerically it means the difference between the two value is 2.01 gram (*Figure 3*). In the experiment of Soratto and his colleagues (2012), silicon foliar fertilisation had no significant effect on TKW values (no significance between control and treated plots, same as in the experiment of Hassan et al.) This is also true for the data in our experiment, although in our case there was a statistically verifiable difference between sulphur and silicon treatment. Hussain and Leitch (2008) conducted an experiment to investigate the effect of sulphur fertilisation on barley and wheat plants, their results showed no detectable significance between TKW values of treated and untreated plants.

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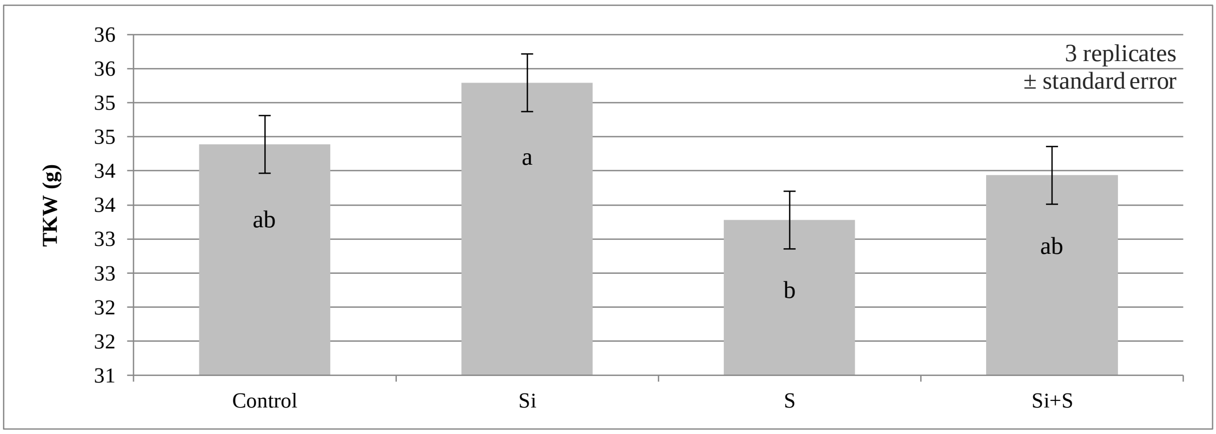
Figure 3. **Thousand kernel weight averaged over treatments (Debrecen, 2023)**



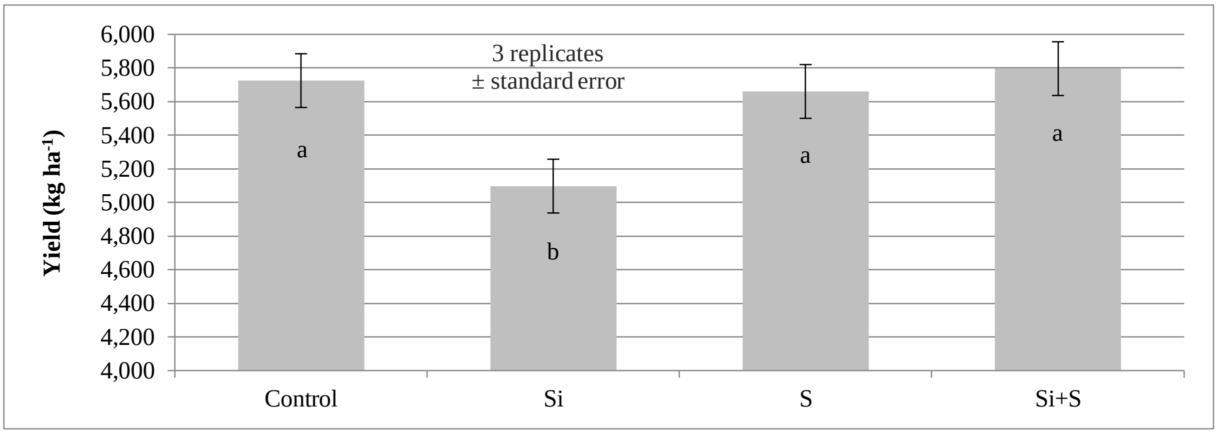
Note: The different letters mean significantly different values at p = 0.05 level

Yield

We obtained different yield results compared to previous years. For example in year 2022 we measured significantly higher yield in plots treated with both sulphur and silicon, and there was no statistical difference between the other treatments. While in the year of 2021, the control plots results was statistically the lowest compared to the other, treated areas (Kutasy et al., 2022). We explained this phenomenon by the weather conditions of the studied year. In this current investigated year, the highest yield was observed in plots receiving the combined treatment, with a value of 5796.47 kg ha^{-1}. This was closely followed by the control plots and plots treated with sulphur, with yields of 5725.06 kg ha^{-1} and 5660.57 kg ha^{-1}, respectively. The yield obtained from plots treated with silicon significantly differed from the results of other treatments, with a yield of 5097.49 kg ha^{1}, as we can see it in *Figure 4.* This meant that plots treated with Si had 0.96% lower yield than the control plots, and 12.06% less yield than the Si+S treatment.

If we look back at our TKW results, it is a quite contradictory phenomenon that although we obtained the highest values in areas treated with silicon, we still achieved the lowest yield results in this treatment. The opposite can be said about the sulphur treatment: while the TKW scores were statistically demonstrably lower compared to the silicon-treated TKW results, the yield of the parcels treated with sulphur were significantly higher than those treated with silicon. This trend contradicts the results obtained during the correlation analysis, which we will discuss in the next section. In the case of yield, based on the literature (and our own experimental results), silicon had a positive effect on yield. (Artyszak, 2018; Hassan and Alsulaiman, 2023). In their experiment, Barczak and colleagues (2018) measured significantly higher yields after sulphur fertilisation compared to unfertilised plants, with no difference in yield between the tested doses. However, not only because of its significant effect on yield, but also because of its other positive properties (promotion of micronutrient uptake), it is worth including in a nutrient supplementation plan.

Figure 4. **Yield averaged over treatments (Debrecen, 2023)**



Note: The different letters mean significantly different values at p = 0.05 level

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Pearson's correlation coefficient

The relationship between the various measured parameters was determined using Pearson's correlation coefficient. For example, in Cociu's research (2018) we can see that they found a strong positive correlation between the number of spikes per m² and the yield in wheat cultivars. Eroshenko and his colleagues (2021) found out that in spring barley there was a strong negative correlation between the TKW and the yield.

The results in our study revealed generally weak correlations, typically with values below r= ±0.2, which were considered significant. The strongest correlation was observed between yield and TKW – where r=0.328 – as well as between the number of nodes and the number of spikelets, (r=0.273). These values are considered to be moderate (*Table 3*).

Table 3. **The result of the Pearson correlation coefficient values between crop productivity elements and yield (Debrecen, 2023)**

		Number of panicle per m²	Number of panicle nodes	Number of spikelets per panicle	TKW	Yield
Number of panicle per m²	Pearson Correlation	1	-0.007	-0.080**	-0.063**	0.077**
	Sig. (2-tailed)		0.756	0.001	0.008	0.001
	N		1741	1741	1741	1741
Number of panicle nodes	Pearson Correlation		1	-0.273**	0.058*	0.035
	Sig. (2-tailed)			0.000	0.015	0.145
	N			1741	1741	1741
Number of spikelets per panicle	Pearson Correlation			1	-0.076**	0.064**
	Sig. (2-tailed)				0.001	0.008
	N				1741	1741
TKW	Pearson Correlation				1	0.328**
	Sig. (2-tailed)					0.000
	N					1741
Yield	Pearson Correlation					1
	Sig. (2-tailed)					
	N					

**. Correlation is significant at the 0.01 level (2-tailed).

CONCLUSIONS

Our results shows that silicon and sulphur fertilisation could have a great impact on arable crops too. It's an interesting fact that even though we measured the highest TKW in the Si-treated plots, we measured the lowest yields in the Si-treated plots, even though we measured the strongest positive correlation between these two parameters in the Pearson's correlation test. We found that the sulphur treatment caused a significant increase in the number of panicle nodes, and we measured the lowest number of panicles per square meter when we used silicon as fertiliser. It's interesting that both silicon and sulphur treatment caused significantly higher spikelet number, but when we applied them together it resulted slightly higher number than the control plot, even though the difference between Si and Si+S wasn't obviously significant. Talking about the yields, the Si-treated plots showed significantly lower results compared to the other treatments. Although it was not statistically different from the S and control applied plots, the highest yields were measured in the Si+S plots.

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