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EFFECTS OF SILICON AND SULFUR FERTILIZATION ON ABIOTIC
STRESS RESISTANCE AND PRODUCTIVITY OF SPRING OAT (*Avena*
***sativa* L.) VARIETIES**

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EFFECTS OF SILICON AND SULFUR FERTILIZATION ON ABIOTIC STRESS
RESISTANCE AND PRODUCTIVITY OF SPRING OAT (*Avena sativa* L.)
VARIETIES

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1. INTRODUCTION

Agriculture is facing higher challenges during the last century, particularly regarding to the perspective of a fast-growing population. To address the scary food crises, agriculture has to evolve to sustain the food and feed demand for humans and animals. Therefore, the global trend continuous and extensive research are being conducted on cereal crop production to enhance yield performance and grain quality parameters. In order to eliminate food crises in the future the expansion of agricultural land is necessary and, the selection of the best performing varieties, as well as the implementation of best agricultural practices. A multidisciplinary approach is needed to challenge the food security for the human population, starting with genetic improvements, sustainable arable land management and technology adoption. In order to mitigate any risk in a global approach and supply sustainable food for upcoming generation, priority in agriculture production is paramount (Fróna et al., 2019).

Cereal are the most important crops for human diets (Laskowski et al., 2019), industrial processing and animal feeding (Wrigley, 2017). During the past 3 decades, the world highly produced cereal crops in this order: maize, rice, wheat, barley, sorghum and oat (*Avena sativa* L., *Zea mays* L., *Oryza sativa* L., *Triticum aestivum* L., *Hordeum vulgare* L., *Sorghum bicolor* L., and *Avena sativa* L.) (Ma et al., 2021). Oats has a significant role in globally crop production, where around 10 million hectares are planted in recent years. Oats in the livestock industry provide a crucial feed for animals which can be used in different forms such as hay, green, and concentrated form. While oat flour or food products produced from it have a rich nutritional value that provides a very useful food in human diet (Loskutov et al., 2021).

According to Rhadari and Hoseini (2012), there are several environmental stresses involving salt, chilling, and drought stress which can have different effect on plant growth and production. The stress effect is usually identified as a reduction in plant growth and photosynthesis, and this stress is connected with alternation in nitrogen and carbon metabolism. Nowadays the essential environmental stress is drought stress, which affects agricultural yield and productivity worldwide. Under rigorous water stress circumstances caused by drought or high salinity, the process of growing stops completely in plants, and all the solutes will be accumulated in crop cells (Barnabás et al., 2008), as well as temperature stress (Porter and Gawith, 1999) and nutritional stress. Although plants can adjust to drought

stress by their physiological, morphological, and metabolic means (Rhadari and Hoseini, 2012), external agronomic interventions are inevitable.

Soil nutritional parameters due to climatic conditions are resulting in potential mineral matrix changes where the weather tolerant minerals are accumulated. Furthermore, soil fertility functions are being degraded, and reliance on external nutrient inputs is expected to increase. It has been frequently stated that, the soil characteristics are being modified by the climatic variability. Soil based parameters, such as carbon content, even it is hard to modify can be verified by the scale of climatology, while fast response due to climatic variation can be detected in soil erosion specifically in precipitation measurements (Gelybó et al., 2018). It seems that the soil quality has an implication for food security due to ecosystem management. The main factors for the air, water, and heat management of soil profile are hydraulic conductivity, water retention, and soil composition (Tehrani et al., 2025). However, researchers have confirmed that stress of the soil moisture affects the soil parameters and crop production (Mills et al., 2014). This implies that exogenous application of any form of fertilizers into the soil could have a great role in both improving soil productivity and cereals' grain yield as well.

Yield potential depends on many factors such as growing area, cultivars, climatic conditions, and it is moderated by other factors such as stress tolerance and diseases, water, nutrient supply, agrotechnical factors, and the type of genotypes, which are the major factors for plant height and grain yield (Karing et al., 1999). Furthermore, there can be significant differences in productivity among oat varieties (Forsberg and Reeves, 1995).

According to Li et al. (2005), about twenty percent of crops worldwide are irrigated. Water is an essential factor for cereal growth and production, where the main way to have sustainable cereal production is to improve water use efficiency (Du et al., 2010) Plants' water requirements are expressed in millimeters of water depth needed for evapotranspiration (Pereira and Alves, 2013). Water is the major factor for oat development from seed germination to the last phase development and maturity, where the main factor for lower crop productivity it is drought stress. Tahir et al. (2014) examined the effect of irrigation at different crop developmental phases of oats under different nitrogen (N) and phosphorus (P)

supply. They reported that irrigation intervals had a significant effect on number of tillers, tiller height, number of leaves, and green fodder yield.

According to Sinclair and Rufty (2012), yield potential is associated with available water and nitrogen supply. Under high water stress, the oats response to nitrogen is small, and the yield potential is low. While the water quantity increased, the response to the nitrogen also increased. Water stress has a high impact on reducing crop productivity, which makes the water vital component for crop growth from seed germination to the maturation phase, where the accurate amount of water is a basic requirement for water and soil management practices to increase agricultural production (Zhang et al., 2024). Plant growth in soil is highly dependent on biotic and abiotic factors. The best results for yield productivity are influenced from the technological level, varieties, irrigation, nutrient supply and biofertilizer (Han et al., 2006). In terms of nutrient supply sulfur has a crucial role in the formation of vitamins, cysteine, methionine, sulpholipids, and proteins. Furthermore, sulfur application can improve the plant's growth and specifically the yield productivity (Narayan et al., 2023; Koirang et al., 2022). Generally, nutritional value and plant yield production are significantly influenced by the sulfur application (Aula et al., 2019). Generally, few studies have elucidated the response of oat to foliar nutrient supply. For example, nitrogen, sulfur and carbon in plant tissues as well as Mn, Ni, Ba, Ca, Cu, Fe, K, P, Mo, Na, Zn and Pb in oat grains were improved by foliar nutrient application compared to the control (Kutasy et al., 2023). Likewise forage nutritional values were optimized by biofertilizer application, making biofertilizers key in sustainable production of oat (Aguirre- Córdova et al., 2021). Overall, the interaction genetic factors and external factors climate conditions, nutrient supply of fertilization affected yield and quality of oats. To determine and clarify all of these factors, research was conducted where the influence of foliar fertilizers, environmental parameters and varietal divergences of spring oats were tested. Specific objectives were to:

- a) Evaluate the effect of sole and combined foliar treatment of silicon and sulfur on the physio-morphological parameters and yield of spring oat.
- b) Assess the impact of sole and combined foliar treatment of silicon and sulfur on the grain microelement and microelement concentration of spring oats.

- c) Assess the effect of varieties on the physio-morphological parameters, yield, and grain microelement and microelement concentration of spring oats.
- d) Analyze the effects of growing year and different environmental conditions on the physio-morphological parameters, yield, and grain macroelement and microelement concentration of spring oat.

2. LITERATURE REVIEW

2.1 The importance of oat production

Oats have been involved in the food and feed industry for animals and human purposes for decades because of their health and nutritional benefits (Tosh and Miller, 2016). As a food, it has been shown to extend satiety, ameliorate blood glucose response, decrease the risk of cardiovascular diseases, hypocholesterolemia, and anticancer properties (Tosh and Miller, 2016; Rasane et al., 2015). Oats are the most popular and widely used cereals for animals because of their unique nutritional value, which contains low energy content, high levels of protein, fiber, and minerals. Compared to other cereals, oats contain more protein. The value of amino acids has been indicated in ideal diets for horses, poultry, and swine (Rosentrater and Evers, 2018). According to Hareland and Manthey (2003), the first oatmeal was sold in the 19th century in United States of America, mostly it was recommended by pharmacies as a food for the infirm. Furthermore, the thermal oat processing develops an aroma and flavor that provides application in baked and cereal food products. The flour from oats is utilized as an important ingredient in different food products. For the lactose intolerance people who cannot produce the lactase enzyme, they can use an oat milk drink. Furthermore, oats whole grain consumption has recently been considered to have several health advantages, such as anticancerous properties, hypocholesterolaemic, and is an appropriate food for celiac patients (Rasane et al., 2015)

Oats originated from the Poaceae family that occurs at three ploidy levels, diploid, hexaploidy and tetraploid with seven chromosome numbers. The *Avena* genus was established in 17th century and contains around 70 species (Arendt and Zannini, 2013). The main types of oats produced in the world market are part of the hexaploidy species: white and red oats (*Avena sativa* L. and *Avena byzantine* C.), Ethiopian oats (*Avena abyssinica*), black oats (*Avena strigosa*), sterile oat (*Avena sterilis*), and naked oats (*Avena nuda* L) (Jones et al., 2024; Gorash et al., 2017). According to Kutasy et al., (2021), in Hungary, the winter and spring oat varieties that originated from *Avena sativa* L. are cultivated across the country. From winter oat varieties, the most cultivated are GK Arany and Mv Hópehely, while from spring oat varieties are Lota, Panna, Mv Ménes, GK Pillangó, and GK Kormorán. The main classification categories for *Avena* L. species are: cultivated, segetal and wild species.

Over the decades, cereals have always played a crucial role in ensuring human survival in first decades and later in the human diet. At the same time, cereal production has been accompanied by continuous stress from plant diseases, climate factors and agricultural practices. Plant producers and researches always have been trying to minimize or manage these stresses, which still remain a major factor in agricultural production. From the existing data even in prehistory and early history from the archaeological facts oats remain one of the most important cereals (Moore-Colyer, 1995).

Global oat production in the last decade has ranged from 19.46 to 25.96 million metric tons (Figure1).

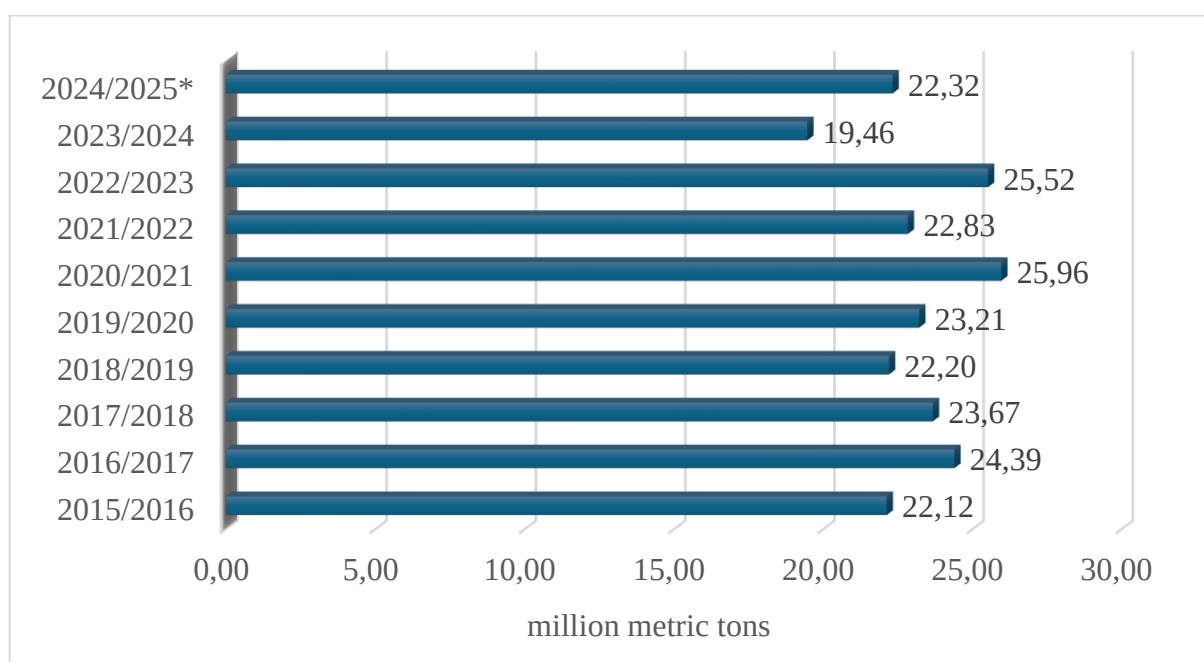


Figure 1: Worldwide oat production from 2015/2016 – 2024/2025 (USDA Foreign Agricultural service)

In 2023, Europe produced the largest amount of oats, accounting for 31% of total oat production globally, followed by Russia with 17%, Canada 16% and other countries with lower production. Furthermore, from 27 EU countries in 2024, Poland was the largest producer with 26% of total European production, followed by Finland 14% and Spain 13%, while the remaining 24 countries produced only 47% of total oat production in the EU. However, Hungary ranks 15th in Europe in oat production and contributes only 1% of total oat production in EU countries (Figure 2).

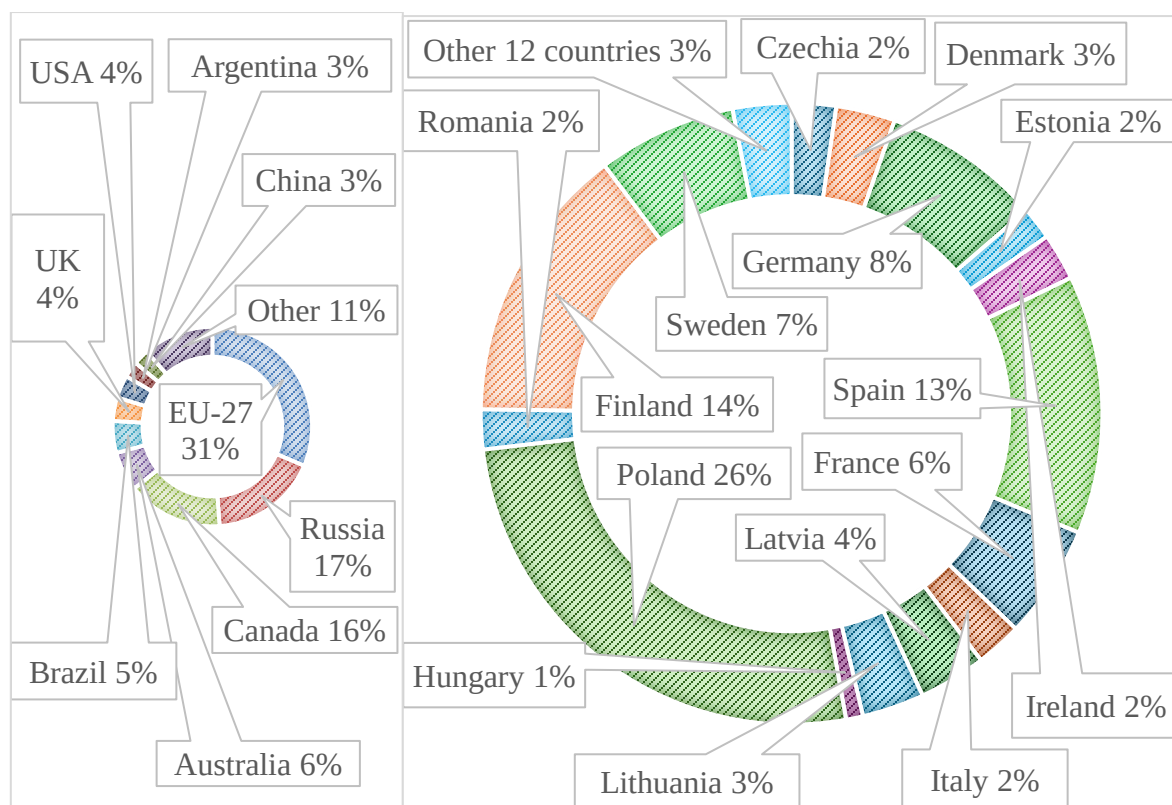


Figure 2: Worldwide oat production in 2023 (left) and EU leading oat producers in 2024 (right) (US Department of Agriculture: Index Mundi) (Eurostat, 2024)

Oat production in Hungary from the 1990s and the present time has had large fluctuations, where the highest production was achieved in 2004 with a total of 217376 t of oats produced in the country. The lowest production was recorded in the year 2022, with a total of only 38387 t produced within that year. In fact, there has been a slight rise in oat production for 2023 and 2024, recording 60583 t and 78635 t, respectively. Considering the extremely low production of oats in Hungary recent years, this gives a great opportunity for future research to determine the best oat varieties and agrotechnical production (Figure 3).

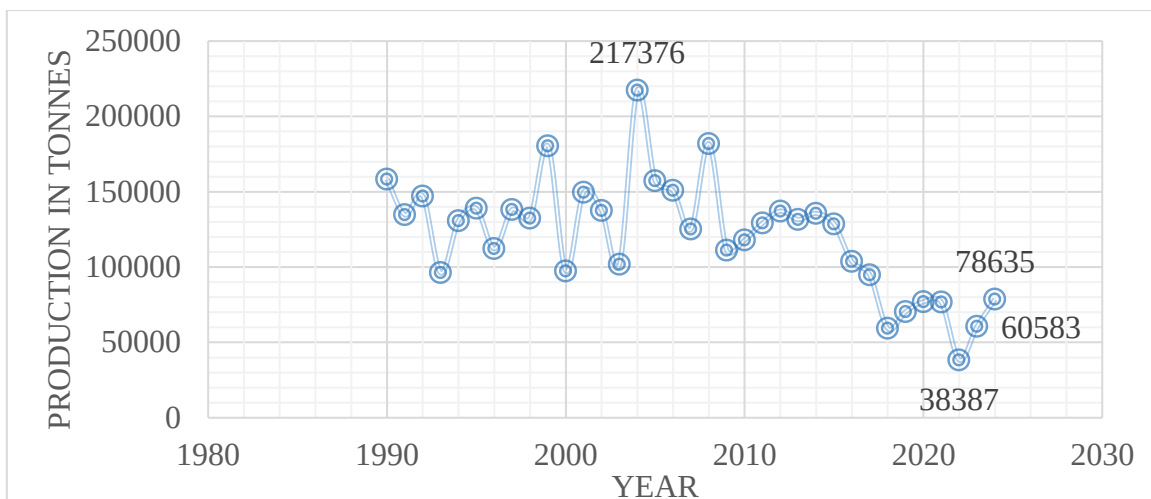


Figure 3: Hungarian oat production 1990-2024 (Hungarian Central Statistical Office)

Oat yield in North America is 30% lower than in European countries, which also exhibits a higher yield compared with African countries. The average annual production was 13 million tons in the 1960s, increasing to 23 million tons by 2013 (Boczkowska et al., 2016). Mainly oats are cultivated in cool temperature conditions. Russia is the main producer, followed by Canada, the United States of America, Finland, Poland, Austria, and Argentina. The majority of oats production is represented by husked oats (Zwer, 2004). In 2011, Europe produced 60% of worldwide production, around 11.19 million metric tons. Furthermore, the average yield in the Baltic States was 2 t/ha, in Scandinavia 3-5 t/ha, in the United Kingdom 6 t/ha, and in Ireland over 7 t/ha (Marshall et al., 2013). According to the Hungarian Central Statistical Office, the average oat yield in Hungary has shown slight fluctuations over recent years. In 2022, the average yield was reported at 2.9 t/ha, which increased to 3.2 t/ha in 2023, and a slight decrease was observed in 2024, with the recorded yield at 3.1 t/ha.

2.2 The influence of fertilizers on physiological parameters and oat production

The application of fertilizers containing different nutrients, either by foliar or soil application, elicits different effects on oats production and physiological characteristics. For example, in terms of soil application method, the application of N:P₂O₅ at 150:60 provided adequate nutrients for growth of oat resulting into better performance as compared to the control in plants leaf area (128 cm²), number of tillers per meter square (336), crop height (146.3 cm), and number of leaves/plant (6.867) (Waheed et al., 2012). According to Ju et al. (2022), 90

kg ha⁻¹ nitrogen application optimized oat photosynthesis traits, including stomatal conductance, SPAD, photosynthetic value, and LAI, while 80 kg ha⁻¹ nitrogen application was recommended as suitable for oat production in agroecological zones with similar environmental conditions. Meanwhile, the sulfur interaction with different levels of fertilizers significantly increased the crop height (107.6 cm) (Mhmood and Mahmoud, 2021). Also, 120 kg ha⁻¹ nitrogen application significantly improved the lengths of oat tiller for 22% as well as crop height for 36.9 cm compared to the control (Midha et al., 2015). According to Kaur and Goyal (2017), nitrogen significantly influenced the growth characteristics. Furthermore, phosphorus fertilization had an effect in the early season of oat growth (Mohr et al., 2007). Nitrogen application in split doses of 40 + 40 kg ha⁻¹ had higher leaf area (64.1 cm²) and plant height of 70.8 cm, while two-time management of 20 kg N ha⁻¹ had higher photosynthetic rate of 11.6 mmol⁻²S⁻¹, fresh weight of 16572 kg, and tiller number per plant of 6. The same report showed that at the booting stage, 18 kg N ha⁻¹ had a maximum NDVI value of 0.68 compared to all other treatments (Shah et al., 2021). On the contrary, there was no response to nitrogen fertilization by top dressing in white oat when monitored temporarily by use of spectral indices, including NDVI and leaf chlorophyll index (Barbosa and de Faria, 2020). The influence of nitrogen application on the oats LAI and SPAD measurements was evident, especially with increased rates (Panasiewicz et al., 2017). Fertilization with nitrogen at 80 kg ha⁻¹ influenced the growth characteristics: crop height of 111.5 cm, leaf area of 36 cm², number of tillers per m² of 204.4, panicle length of 43.0 cm, and grains per panicle of 55.1 (Said et al., 2019). Jarecki et al. (2025) explained that the sewage sludge composts produced higher SPAD than park waste composts, albeit all fertilization treatments enhanced plant height.

In terms of foliar application method, Alrubaiee et al. (2019) resulted that the urea or potash treatments influenced the tillers and spike number compared to untreated. In other aspects, foliar application of potassium at 3 g L⁻¹ shortened the physiological maturity period to 126.5 and 122.4 days, while the zero control resulted in 130.9 days, to reach physiological maturity (Ali et al., 2025). Similarly, application of NPK fertilizer at the concentration of 2 g L⁻¹ reduced the days to reach physiological maturity after planting from 125.6 to 120.3 days, and produced promising results in terms of plant height. Meanwhile, 1 g L⁻¹ had better performance in terms of leaf area of 41.15 and 41.4 cm² in both seasons, while both

concentrations 1 and 2 g L⁻¹ produced considerably higher average chlorophyll content of 28.88 and 27.83 SPAD units in the two seasons, respectively (Al-Bakri and Lehmood, 2024). Tobiasz-Salach et al. (2016) noted that the canopy architecture of oat is diversified by foliar fertilizers, exhibited by increased mean tip angel and leaf area index. Specifically, Basfoliar 36 Extra produced the highest mean tip angle and leaf area index. Al-Sultani et al. (2023) demonstrated nano potassium to significantly improve chlorophyll index, crop height, flag leaf area, and tiller number. For example, a 2 g L⁻¹ concentration had the highest SPAD mean of 55.3 compared to the control which had a SPAD of 51.1. Summary analyses of literature reveal the latest oat research tailored to enhancing productivity and nutrient use efficiency under climate change (Figure 4).

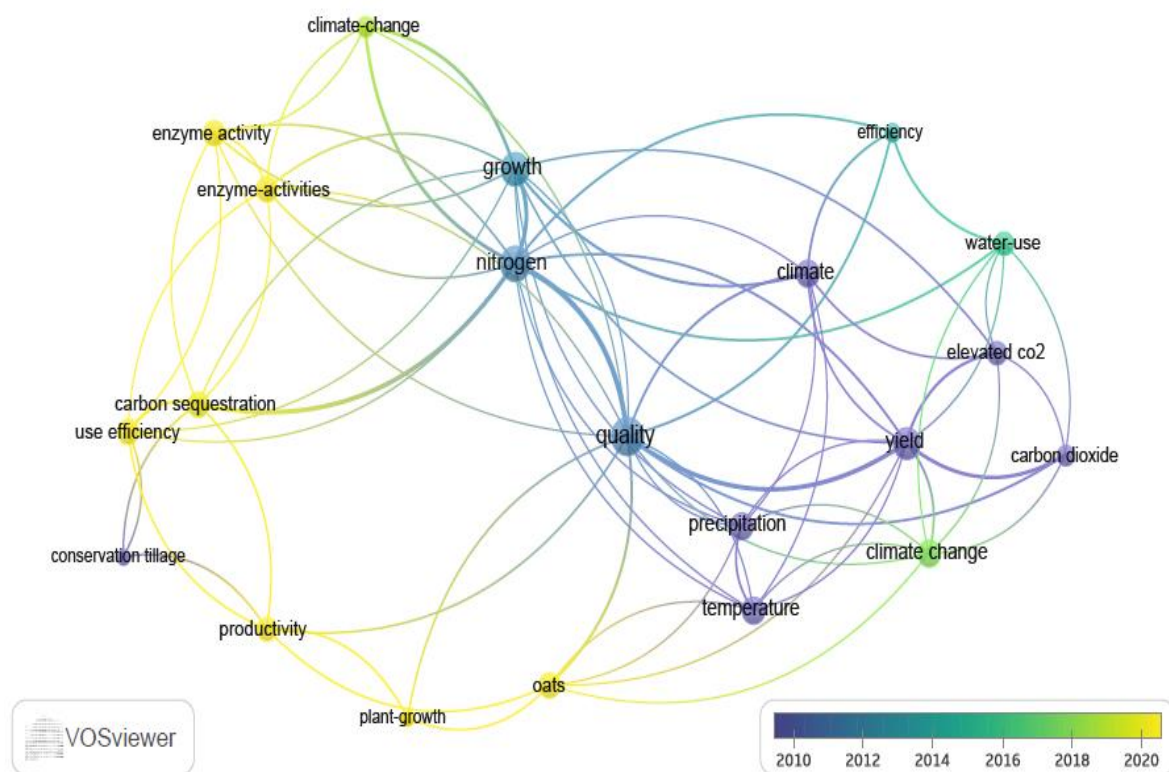


Figure 4: Latest research direction on fertilization and oat production

Note: Vosviewer analysis from literature extracted from web of science.

2.3 The influence of fertilizer application on oats grain yield and its components

The productivity of oats is influenced by the fertilization type with direct effect on grain yield, or soil properties which in turn affect yield (Vasileva and Kostov, 2018). Several authors have reported results on the effect of foliar nutrient application, including sulfur. For example, foliar application of urea or potash in high amounts produced the highest harvest index compared to no treatment foliar application. In fact, in comparison to no fertilizer application, urea increased panicle number from 394.8 to 416.5, with 3.95 t ha⁻¹ yield productivity (Alrubaiie et al., 2019). According to Ali et al. (2025), significant variation was in the number of panicles m⁻² with varying rates of potassium application, with 3 g K L⁻¹ recording the highest panicle number (326.33 and 327.85 panicles m⁻²) in the two seasons compared to 308.70 and 302.58 panicles m⁻² in the control. The same study showed that the highest yield of 5.8 and 6.2 t ha⁻¹ was obtained at 3000 mg K L⁻¹ compared to 4.3 and 5.0 t ha⁻¹ in the control in the two seasons, respectively. Relatedly, Henrichsen et al. (2022) noted that nitrogen application at 78 kg ha⁻¹ in the soybean/oat system produced a yield of 3 t ha⁻¹. The study showed that linear expression of grain yield increases with increasing urea and liquid sources of fertilizer, though the acquisition costs could be a limiting factor for N-top® liquid source nitrogen, which is already validated. Also, a study by Devi et al. (2019) revealed a significant yield improvement due to nitrogen application as well as the number of oat spikelets, grain and m² panicle. On the other hand, foliar spray of zinc improved yield and yield components, with 50 mg Zn L⁻¹ producing grain yield of 6.24 and 6.06 t ha⁻¹ in the two seasons (AlRawi and Abood, 2021). Tobiasz-Salach et al. (2016) reported increase in yield due to foliar fertilizer with the highest yield recorded under Basfoliar 36 Extra and Basfoliar 12-4-6+S application, as well as positive effect on panicle grain number, panicle grain weight, and 1000 seeds weight. In terms of sulfur and silicon application, Forgács et al. (2024) revealed that sulfur application recorded 590 spikes, silicon 462 spikes, sulfur + silicon had 492 spikes, and 533 in the control. According to Kutasy et al. (2021) silicon and sulfur treatments had higher yield though not significantly different from other treatments in year 2022 experiment, deviating from the results of year 2021 where significant differences were evident.

Based on soil application, Zhang et al. (2025) accentuated that optimal fertilizer rate of oat varies contingent on crop uptake capacity and field fertility condition. These are essential for understanding oat nutrient use efficiency improvement and fertilizer management in the field. A study by Mhmood and Mahmoud (2021) showed that 180 kg N ha⁻¹ resulted in 3.7 t ha⁻¹ yield production. Similarly, Beltrán-Paz et al. (2024) revealed 49.2% yield improvement by 138 kg ha⁻¹ nitrogen application. May et al. (2020) explained that farmers aiming at higher yield started applying nitrogen in the 90 kg ha⁻¹ amount to oat crops, though several researchers consistently did not follow the exact nitrogen rate application. A study by Ramadhan (2024) revealed that 280:180:200 and 210:135:150 kg NPK per hectare resulted in the highest yield and yield components of oats. However, the same study echoed that it is critical to follow fertilizer guidelines since both inadequate doses and increased fertilization do not necessarily boost oat productivity or output. In this regard, Lin et al. (2025) emphasized the need for maximum thresholds of nitrogen and phosphorus application. Earlier, Mohr et al. (2007) reported that a low and moderate nitrogen treatment significantly influences the yield, with optimum yield obtained at 100 kg N ha⁻¹. However, increasing nitrogen treatment showed a lower individual grain mass and reduced grain fullness. Also, yield increased only in two out of six site years while KCl caused a small improvement in yield (88 kg ha⁻¹), as well as kernel plumpness and kernel weight on soil rich in potassium. Qiao et al. (2024) reported in their study a significant yield improvement as a result of nitrogen application at optimal rates in the range of 90 and 180 kg ha⁻¹ in three different phenological maturity stages: early, mid, and late for oat genotypes. Early maturing variety performed the best with 2.2 t ha⁻¹ at N3 treatment, while the mid and late maturing oat had yields of 2.5 and 2.9 kg ha⁻¹ under N4 treatment. The study emphasized that since late maturing oat coincided with the hot and rainy season, it was appropriate for planting in the dryland areas. A meta-analysis by Mao et al. (2025) confirmed a 36.2% oat yield increment due to fertilizer application, and established that balanced phosphorus, potassium, and nitrogen fertilization enhances grain yield irrespective of large spatial and temporal variations. A study by May (2017) showed that application of phosphorus constantly enhanced grain yield over 3 years at several sites by 3.4%, and decreased wild oat seed by 0.5% in the harvested grain. Also, earlier, Mohr et al. (2007) demonstrated that potassium influences oat grain yield in some cases. A study by Ju et al. (2022) showed that nitrogen

application significantly influenced the oat yield components, while at the same time, increasing rates of fertilizer caused a reduction in yield. Meanwhile, grain weight was sustained as nitrogen level applied at GS50 increased, with a reduction recorded at earlier application, with no effect on the grain yield (McCabe and Burke, 2022). Koireng et al. (2022) confirmed the positive efficacy of 50% nitrogen from vermicompost and 50% inorganic nitrogen to sustain high seed yield in oat and chickpea intercrop. Another study showed that phosphorous fertilization increased the yield of early maturing variety Veli while reducing the 1000 grain weight of the varieties tested (Saastamoinen, 1998). Nutrient supply by fertigation showed the best grain yield performance with 5.6 t ha⁻¹ under nitrogen rates of 45 kg ha⁻¹ and biomass yield of 20,731 kg ha⁻¹ at 88 kg ha⁻¹, respectively (Coelho et al., 2019). Wojtacki et al. (2025) modelled the influence of climatic and agronomic characteristics on the grain yield of both hulless and hulled oat. Application of nitrogen at the rate of 60 kg ha⁻¹ increased yield by 41% for hulless and 35% for hulled oat. While the application rate of 120 kg ha⁻¹ influenced the yield by 11% in hulless and 13% for hulled oat. The report also showed a higher nitrogen use efficiency of one kilogram of nitrogen to produce 20 and 15 kg per grain in hulled and hulless oat. Application of chemical fertilizer (N₉₀P₉₀K₉₀) improved yield by 19.3% (+0.93 t ha⁻¹), which was the most effective among all the treatments evaluated. Additionally, nitrogen fertilization at 80 kg ha⁻¹ had performance supremacy with 9.9 t ha⁻¹ yield productivity (Karbivska, et al., 2025). Also, the yield components, panicle grain number, thousand grain weight, and grain weight were enhanced by both mineral and compost fertilizers (Jarecki et al., 2025).

The influence of sulfur fertilization on cereals has been studied by many researchers. The most important abiotic stresses for crop productivity are sulfur-dioxide (SO₂) and drought (Li et al., 2022). However, the positive performance is attributed to sulfur due to its effectiveness, and its ability in the prevention of drought stress, chlorophyll synthesis, uptake of NPK, cysteine, and methionine amino acid compounds (Shah et al., 2022). Sulfur application significantly increased the number of spikelets with an average of 5.02 nodes, followed by sulfur and silicon combination, and only silicon by 4.7 and 4.8, respectively. In terms of a thousand kernel weight, although there were no considerable differences, silicon had a slightly higher value (35.3 g) compared to 33.9 g under sulfur and silicon combination, as compared to 34.4 g in the control (Forgács et al., 2024). Barczak et al. (2018) noted that

sulfur improves micronutrient uptake in oat and consequently grain yield. Generally, from the synthesis of the above literature, it is evident that there is scanty literature on the application of sulfur and silicon in oat production, making this a strong knowledge gap that this study bridges.

2.4 The foliar fertilizers effectiveness on grain macronutrients and micronutrients content of wheat and oat

Crop management practices, including fertilizer application, affect nutrient levels or concentrations in crop parts such as grains (Wortmann et al., 2018). According to Smith et al. (2017), phosphorous fertilizer improved magnesium by 4%, manganese by 75%, and phosphorus by 18%, and reduced copper and zinc by 22% and 26%, respectively, in wheat grain. On the other hand, increased nitrogen content at the onset of favorable conditions decreased potassium, calcium, magnesium, manganese, and zinc content. According to Wang et al. (2025), substitution of organic fertilizer by 15% improved wheat iron and zinc bioavailability and general nutritional quality without compromising yield. Also, the NPK foliar fertilization optimized grain content by 14.9%, NPK + copper by 13.0%, and NPK + copper + zinc + manganese improved copper and zinc in grain by 22.6% and 17.7%, respectively (Stepien et al., 2016). Svecnjak et al. (2013) analyzed the influence of nitrogen application on trace element content in wheat cultivars. Results showed an improvement of trace elements by 23.0%, 15.1%, 13.2%, 19.7%, 9.2%, 14.0% for cadmium, nickel, copper, manganese, zinc, and iron, respectively, while sodium was not affected by high nitrogen rates. Another study revealed that nitrogen fertilization (90 kg ha⁻¹) reduced potassium, phosphorus, and calcium accumulation in the wheat grain with zero and 45 kg N ha⁻¹, suggesting that farmyard manure influenced the decline of micronutrients over time (Shiwakoti et al., 2020).

A number of studies have been undertaken on oats. Earlier, Mohr et al. (2007) established that potassium has an impact on oat grain quality in some cases. Also, a study by Pisulewska et al. (2009) showed that in the Akt variety, NPK dose improved magnesium and iron content with limited variations in oat grain concentration with iron, copper, zinc, and manganese between the Akt and Dukat varieties. Cultivar Akt was richer in mineral nutrients, especially potassium, phosphorus, magnesium, iron, calcium, and zinc, than cultivar Dukat. However,

the study generally showed a decrease in micronutrient grain content due to high doses of mineral fertilizer. Another study revealed that even though the sulfur requirement of oat is low, its impact on grain yield was positive, producing a yield increment of 7.8%, despite the absence of significant differences between fertilized and unfertilized treatments. Additionally, sulfur application improved copper and manganese content as well as all micronutrient uptake except iron. Conversely, nitrogen fertilization affected magnesium, calcium, and phosphorus of oats except potassium. Specifically, magnesium and calcium were high, while calcium was lower. Generally, the study showed variation in micronutrient concentration also depended on wetter and cooler year 2010 and warmer and drier year 2011. Also, earlier, Chalmers et al. (1998) measured a significant improvement in grain nitrogen content by 0.12% due to nitrogen fertilizer application at the rate of 40 kg N ha⁻¹. A study by Barczak et al. (2018) presented the impact of sulfur on reducing the ratio of iron to manganese. From the literature reviewed, it's evident that limited studies have explored the influence of sulfur and silicon on the micronutrient and macronutrient concentrations of oat and other related cereals.

The global food production it is facing the climate change in the last century due to extreme temperatures and low precipitation, which are affecting the drought severity. The changes in environmental conditions and prolonged drought severity are influencing the food production, from the germination, vegetative phase, and the grain nutritional composition, which are forcing improvement in the agricultural strategies to have quantitative and qualitative production (Hakala et al., 2020). Sole or combined silicon and sulfur foliar treatment improved the grain production and quality of cereals specifically under drought conditions. From our experimental in spring oats we can have a better information through the foliar application of silicon and sulfur on the grain elemental composition. Sulfur has a significant role in the assimilation of nitrogen and as part of aminoacids, enzymes and protein composition. The dosage of sulfur through the redox and metabolic activity results as an important factor in the accumulation of chemical elements and utilization of nitrogen, phosphorus, and potassium as internal plant processes (Scherer., 2001; Mehmood et al., 2021). Silicon element has a crucial role on the macroelement uptake. Scientific researchers have reported the role of silicon in the magnesium and phosphorus accumulation in tissues of the crops (Greger., 2018; Schaller., 2021). Specifically, under serious drought

environmental conditions, silicon increases the water content status in crops. From the scientific literature it has been showed that under the climatic conditions with optimal temperature and controlled irrigation, there were no significant phosphorus, magnesium, and calcium accumulation on the wheat grains (Schaller., 2021).

2.5 Effect of genotypes on oat grain growth parameters, yield and quality

Genetic variability of different genotypes of oat influences their performance under different agroecological zones. Midha et al. (2015) indicated a significant difference in growth parameters of oat varieties evaluated. Variety SKO-188 recorded the highest (129.4 cm) plant height compared to all varieties of oat tested, while variety OS-377 had the lowest plant height (90.8 cm). In terms of tiller number, varieties SKO-188 and JO-03-97 produced the maximum tillers per row length compared to varieties JHO-10-2, OL-125 (NC), UPO-10-1, and OS-377. Another study revealed that variety oat 11 had a lower number of panicles (394.9) compared to Shafaa variety which significantly had the highest panicle number (416.3), attributed to an increased number of tillers (Alrubaiee et al., 2019). Alrubaiee et al. (2019) showed the Shafaa variety has a superior performance in terms of tillers and spike numbers. The Carlup cultivar exhibited the shortest time of 126.40 and 122.38 days to reach physiological maturity in both seasons, respectively (Ali et al., 2025). Al-Bakri and Lehmoode (2024) reported for physiological maturity, compared to the other two cultivars, cultivar Carolup reached maturity early in 125.9 and 119.2 days, and also had the best performance with a 1.34 m of crop height during the first season, and the highest leaf area of 39.4 cm² during the next season. On the other hands, cultivar Hamel had the best performance, including chlorophyll of 29.3 and 28.9 SPAD in both seasons. Al-Sultani et al. (2023) reported similarity of tiller numbers for Oat 11 and Jouda oat cultivars. However, for some measurements, such as flag leaf area, index of chlorophyll, and plant height, cultivar Jouda showed significantly the highest values compared to other cultivars. Meanwhile, the plant height of spring oat significantly varied across genotypes, with overall height ranging from 59.1 to 100.8 cm (Djaman et al., 2018).

In terms of yield, Ali et al. (2025) revealed that the highest grain number per panicle of 58.05 and 55.30 were recorded in Carlup and Genzania cultivar, while cultivar Hamel resulted in the grain number per panicle of 50.13 and 50.76 across the two seasons. Similarly, the same

study showed that the highest grain yield of 5.86 and 5.39 t ha⁻¹ was recorded in Carlup and Genzania cultivars, while cultivar Hamel had the lowest yield of 5.04 and 5.16 tons ha⁻¹ across the two cultivation years. Correspondingly, Al-Rawi and Abood (2021) demonstrated a significant difference in the traits of the varieties tested. The highest grain yield and biological yield of 6.3 and 6.2 tons ha⁻¹ and 16.4 and 16.3 tons ha⁻¹ were reported in the Genzania cultivar. Meanwhile, the interaction between cultivars and the application of zinc and potassium significantly improved all the tested traits. Conversely, the thousand grain weight was higher (45.4 g) in the Shafaaa variety compared to 41.1 g in the oat 11 variety, attributed to genetic variations. The same study echoed that the interaction of variety × year × fertilizer is essential for fertilizer uptake and efficiency (Kebede et al., 2024). Also, a three-way interaction of the studied factors exhibited a significant improvement in yield. In the first season, the combination of variety Genzania + 50 mg Zn L⁻¹ + 3000 nm K performed the best (8.3 t ha⁻¹) grain yield, while in the second season, the highest (7.4 t ha⁻¹) grain yield resulted for the variety Hamel combined with 50 mg Zn L⁻¹ + 6000 nm K (Al-Rawi and Abood, 2021). In contrast, earlier, Pisulewska et al. (2009) showed no significant effects in grain yield for the assessed cultivars Dukat and Akt. However, earlier, Ren et al. (2007) noted that there is an opportunity to harvest different crops in a year from the new oat lines that are sown in both summer and spring. Djaman et al. (2018) revealed significant variation in the grain yield among the 28 genotypes attributed to year and genotype effect. The genotypes that had the best performance were G23, G20, G2, G1, and G19, with a mean yield of more than 4.8 t ha⁻¹, while G27, G17, G3, and G13 had the least performance. Neupane et al. (2025) assessed drought severity effects on two oat genotypes, Hayden and Ajay, and results showed Hayden to have a higher yield than Ajay. Another finding established an interaction environment × genotype impact for the measured parameters apart from the number of seeds per panicle. Multidimensional preference analysis showed SA060123 had outstanding performance for yield and 'Minstrel' for harvest index, respectively. (Ma et al., 2017).

2.6 Effect of environmental factors on the growth, yield and grain quality of oat

The abiotic components that limit crop production are drought stress, high temperatures, low precipitation, and high salinity. These environmental, climatic, and abiotic stresses cause different physiological and biochemical reactions in plants, which should be adapted by

plants to continue to exist (Seki et al., 2003). Drought from the abiotic stress influences mostly germination rates, initial development of the seedling, plant growth, yield, and productivity (Oliveira et al., 2020). Oats, wheat, and barley belong to different taxonomies, but they share agronomic and physiological similarities such as responsiveness to stress. Furthermore, the ability of oat varieties to adapt to the environmental conditions depends on several factors, including stress duration, intensity, timing and recurrence (Sadras et al., 2017). Water is the major factor for oat development from seed germination to the last phase of development and maturity, where drought conditions highly influence the crop production globally. A sufficient amount of water at different crop development stages can optimize and increase the effectiveness of metabolic processes in crop cells and better use of mineral nutrients from crops (Jemal et al. 2019).

Physiological mechanisms play a crucial role in protecting the plant from harsh environmental conditions. Drought has a serious effect on crop cultivation significantly affecting growth, resulting in wilted leaves, yellowing, chlorosis, and stunting. Furthermore, drought conditions can affect the photosynthetic organs, metabolic function, structure and function of cells, decrease nutrition absorption rate, decrease transportation rate, reduce plant quality, inhibit plant growth, and plant death (Xie et al., 2021). Screening and estimation of different cultivars under abiotic stresses, such as drought, based on physiological factors, are the main evidence of oats improvement (Song et al., 2025). Furthermore, changing the soluble sugar and protein concentration in the plant cell fluid concentration will be increased, the osmotic potential will be decreased to stimulate absorption of water, preserve cell outgrowth, and to provide cell metabolism and growth (Xie et al. 2021). Sugar plays a vital role in osmotic protection in plants under moderate stress environment conditions as part of reactive oxygen species (Wang et al., 2026). Control of osmotic potential in crops promotes cell development and contributes to crop growth under drought conditions (Keshavarz et al., 2016).

Serious drought conditions damage the cells in those crops, which directly appear on the leaves color (Farooq et al., 2009). Furthermore, different varieties under the same conditions of drought stress have different resistance, where some can show late symptoms of injuries such as wilting or leaf curling and yellowing (Xie et al. 2021). The relative water content

results in the available water deficit in the crops under serious drought conditions, which are reflected in physiological phases. Furthermore, the relative water content is often considered an effective and comprehensive indicator for discovering crop drought resistance (Neupane et al., 2025). Therefore, the response of oats (*Avena sativa* L.) to drought conditions is essential for the management of dryland and irrigation processes. Oats, in comparison to other cereals, are sensitive to drought stress during the period of anthesis and grain fill (Ehrler, 1969). Mao et al. (2025) explained that a comprehensive understanding of climatic variables and edaphic factors is necessary for the implementation of region-specific agronomic interventions, including fertilizer recommendations. Additionally, the interaction between the environment $\times$ genotype, including the severity and duration of drought, is critical for the identification of oat lines with high adaptation to varying conditions (Neupane et al., 2025). Hakala et al. (2020) noted that at the crop cultivation time, precipitation and temperature patterns are the potential determinants of yield. Oats cultivation and grain are affected by temperature conditions, though comprehensive investigations are required to ascertain the extent of the effect of varying temperatures on grain development. The study also recommended the determination of the optimum temperature that produces potential yield (Ko et al., 2022).

Variation in weather conditions was reported to result in yield variations, with the 2012 season recording the highest yield of 4 t ha⁻¹ attributed to high precipitation levels that coincided with the grain filling period (Barczak et al., 2018). Also, Ali et al. (2025) showed the highest yield of 5.2 and 6.2 t ha⁻¹ across the two seasons. Higher oat yield was reported during the early grain filling period when precipitation was high, while a decrease in yield was reported with temperature above 28 °C during anthesis, suggesting the need for oat varieties tolerant to heat stress (Hakala et al., 2020). Also, during the growth period, elevated temperature caused a reduction in the yield of early maturing variety Veli since this variety was adapted to cool climatic conditions (Saastamoinen, 1998). Petrova et al. (2024) analyzed climate factors and weather patterns affecting oat yield for the period 2014-2021 in Yakutia. Results showed a reduction in oat yields and all yield components, such as panicle length, 1000 grain weight, among others due to climate change, in particular active warming and reduced precipitation. A simulation by Tang et al. (2022) revealed a reduction in soluble sugar content and dry matter yield and an improved concentration of zinc, sodium, magnesium,

sulfur, phosphorus, calcium, manganese, iron, and copper in oat due to an increase in temperature. A case study by Sharma et al. (2023) showed precipitation didn't significantly affect yield, while one degree increase in minimum temperature and maximum temperature reduced yield by 5% and 4%, respectively. Ko et al. (2022) affirmed that temperature at the grain filling stage has a predominant effect on the yield potential. Temperature changes cause an increase or decrease in the weight of dry seeds, length of dry seeds, number of dry seeds, and other yield decreases, and moreover, high temperature causes senescence and substantial loss in grain productivity of oat. This same study showed that environmental signals elucidate oat panicle variable expressivity and spikelet shape variation. For drought effect, Neupane et al. (2025) showed that moderate and severe drought decreased grain yield by 23 % and 41% as compared to the experimental units receiving adequate moisture. Specifically, under all drought levels, variety Hayden recorded higher water use efficiency, relative water content, and grain yield, while variety Ajay had higher panicle number, tiller number, and root to shoot ratio; however, these parameters did not improve leaf hydration and yield under drought stress. From a physiological point of view, temperature increasing decreased spikelet shape development, shoot dry weight, total chlorophyll, and increased activation of MDA, antioxidant enzyme, and soluble sugars (Ko et al., 2022). Although oat responds to abiotic stress by undergoing both physiological and morphological changes, studies involving high altitude are still limited (Jinqiu et al., 2021).

The relationship between different agronomic parameters has been documented differently. Ju et al. (2022) indicated an interaction in stomatal conductance, transpiration rate, photosynthesis rate, stomatal limit amount, intercellular carbon dioxide content, water-use efficiency, panicle length, leaf area index, 1000-kernel weight, and weight of grains per panicle. Forgács et al. (2024) showed an interaction for 1000-kernel weight and yield, as well as number of spikelets and number of nodes. May et al (2017) revealed that panicles per plant as a yield component explained the yield increase arising from nitrogen application. Neupane et al. (2025) revealed a strong correlation in yield components such as seed weight and panicle number, compared to physiological characteristics such as chlorophyll development index, soil, plant analysis and relative water content. Shah et al. (2021) showed a positive interaction ($R^2 = 0.80$) between yield and NDVI at booting and tillering stages. Coelho et al. (2019) reported that NDVI was strongly correlated (> 0.85) for yield and cultivation

parameters in white oats. Specifically, NDVI was correlated with leaf area index, height, panicles (m²), grain weight, grain number per panicle, biomass yield, and grain yield. Analysis of the nexus between different agronomic traits provides insights into assimilate partitioning in oat.

2.7 The silicon treatment method to mitigate environmental stresses on crops

Silicon application significantly influenced the crops to decrease the biotic and abiotic stresses, such as salt, drought, nutrient, freezing, and radiation damage (Wang et al., 2021). In this sense, silicon resulted in great performance in reducing the serious drought conditions in wheat cultivars (Gong et al. 2005). Studies clearly indicate the influence of silicon application in enhancing the crop resistance mechanisms under serious drought conditions, this is due to an antioxidant effect on reducing the oxidative plant stress (Gunes et al., 2007).

Interestingly, wheat cultivars with high silicon accumulation ability showed higher silicon content in their shoots, there were no significant differences in cultivation period under serious drought conditions (Thorne et al., 2021). In comparison, silicon resulted in great drought stress reduction in the tomato and canola, which are characterized by low silicon content. (Wang et al., 2021). Furthermore, the silicon plant content did not affect the drought stress reduction in plants (Katz., 2014). However, silicon influence and benefits in crops are different among the species, varieties, and the cultivation environmental parameters (Wang et al., 2021).

In spite of silicon application, the element is not essential for plant cultivation, but it has a high impact during the crop growth, specifically under serious drought conditions. (Coskun et al., 2016). In wheat cultivars, it improved the seed germination (Hameed et al., 2021). It could probably have been attributed to the increased antioxidant defense and decreased oxidative stress induced by Si (Hasanuzzaman et al., 2019). The silicon application resulted in improvement of biomass and yield in several plant species under serious drought conditions (Chen et al., 2011). This effect improved the total root length, crop height, number of tillers, dry matter, and panicle length (Emam et al., 2014). Furthermore, silico resulted in spikelet sterility reduction and rice yield improvement (Chen et al. 2011).

Exogenous silicon treatment to wheat improved the total stomata conductance, photosynthetic rate, and antioxidant defense (Shaw et al., 2025). It suggested that silicon-based treatment under the serious drought conditions influenced the roots growth and water transportation (Thorne et al., 2021). Therefore, the silicon positive results on the physiology parameters, yield, and grain nutritional content indicate the importance of silicon application in the spring oats cultivars under serious drought conditions.

3. MATERIAL AND METHODS

3.1 Soil Parameters and the Experimental Location

The spring oat experiment was set up during the spring and summer seasons for three consecutive years from 2022 to 2024. The experimental location was set up in Hungary at a part of land for experimental purposes of the Debrecen University with geographic coordinates 47°55'19" north latitude and 21°59'87" east longitude. At the beginning of March, before the first experimental sowing year in 2022, soil analysis was conducted, and the samples were carried out in 10 different soil layers with a depth interval of 20 cm for each layer. The first layer was 20 cm, and the last layer was 200 cm. All the collected soil samples were analyzed at Debrecen University in the Agricultural Laboratory Centre. The laboratory is accredited by the National Accreditation Board of Hungary.

Soil pH was measured in KCl, and in the first layer (0-20 cm) the measured pH was almost neutral (6.93), while in all the other layers it was slightly alkaline. K_A represents the Arany plasticity index type, which was between 45 and 49, representing a medium loam soil texture. The $CaCO_3$ amount in the top soil layers are lower, ranging from 0.52-1.97 while in subsoil layers reached a higher percentage, which showed the calcic horizon availability. The first layer (0-20 cm) is characterized with a good humus content 2.89%, while in the other layers the humus content was decreasing. In the second layer (20-40 cm) it reached 2.89% and in the last layer (180-200 cm) it was 0.41%. Phosphorus showed the highest concentration in the 0-120 cm soil profile, with the greatest P_2O_5 (AL) content detected in the first layer (0-20cm), reaching 1538 mg kg⁻¹. Potassium levels were relatively high in the first two layers (0-40 cm), ranging from 638 to 586 mg kg⁻¹. The NO_3^- (KCl) concentration ranged from 82.2 to 31.6 mg kg⁻¹ in the topsoil layers, while the highest nitrate concentration was recorded the 100-120 cm depth, where it reached 144 mg kg⁻¹ (Table 1). According to WRB (2022) soil system classification and compared to our analysis the land area in our experiment is Haplic Chernozem soil with Calcic Chernozem. The nutrient availability, uptake, and the root development capacity are well developed in our soil experiment, because spring oat roots mostly grow in the first three layers (0-60 cm) depth, and under the serious drought conditions, the maximum root growth can reach the (100-120 cm) layers.

Table 1: The soil parameters in the spring oat cultivation area (2022, Debrecen Hungary).

Soil parameters at the experimental station	Soil profile Layers (cm)									
	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	160-180	180-200
pH (KCl)	6.93	7.46	7.51	7.56	7.55	7.59	7.60	7.73	7.74	7.76
K_A	45	52	52	53	53	56	54	51	50	49
Soluble Salts (%)	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.05	0.04	0.04
CaCO₃ %	0.52	1.45	1.97	2.07	1.86	2.48	2.80	2.90	3.00	3.11
Humus (%)	2.89	2.87	2.63	2.44	2.37	2.55	1.22	0.741	0.445	0.407
P₂O₅ (AL) (mg kg⁻¹)	1538	1149	1020	390	321	954	229	161	105	97.5
K₂O (AL) (mg kg⁻¹)	638	586	366	315	103	421	146	97.8	92.1	87.5
NO₃⁻ (KCl) (mg kg⁻¹)	82.2	53.4	48.5	36.5	31.6	144	98.8	82.5	66.5	54.6
Na (Al) (mg kg⁻¹)	73.7	68.6	66.9	52.1	50.4	107	99.3	91.3	87.7	86.3
Mg (KCl) (mg kg⁻¹)	552	463	352	324	269	584	694	664	540	450
S (KCl) (mg kg⁻¹)	14.1	7.31	3.69	3.38	2.43	4.60	47.8	39.6	36.4	32.6
Mn (EDTA) (mg kg⁻¹)	25.4	25.2	21.7	15.6	13.2	17.6	15.4	10.2	9.36	7.96
Zn (EDTA) (mg kg⁻¹)	2.77	2.24	1.84	1.36	1.21	2.19	1.21	1.13	0.851	0.726
Cu (EDTA) (mg kg⁻¹)	1.27	1.15	1.03	0.967	0.952	1.09	0.555	0.533	0.345	0.297
Soluble Si (mg kg⁻¹)	35.8	28.0	23.0	6.65	5.66	14.8	3.96	3.18	3.74	3.09

Note: KCl: potassium-chloride; K_A: Arany-type plasticity; AL: ammonium lactate-soluble; soluble; EDTA: Ethylenediaminetetraacetic acid.

3.2. Characterization of the crop years in the experimental years (Debrecen, 2022-2024)

The experimental area of the Debrecen University measured the precipitation and temperature on a daily basis for the experiment part, and all of the data were given by the Observatory Centre for Agrometeorological Precision Farming R&D Services, FAFSE, at the University of Debrecen in Hungary.

The cultivation period of spring oats extends from March to July, while precipitation and temperature showed high variation both within and between growing seasons (Figure 5). The 2022 season the temperature was lower during the germination 5.2 °C, compared to the 2023 and 2024 seasons, with an average of 7.5-10 °C, respectively. Precipitation during the

cultivation period also showed substantial differences both within and between growing seasons. The 2022 year was characterized by serious drought conditions while the lowest precipitation rate was detected during the March period with a total mean of 3.5 mm during that period. The cultivation season of 2023 was characterized by the best climatic conditions, where the highest amount of precipitation was during June, with a total average of 122.5 mm. The spring oats had a sufficient precipitation amount for their development at the final growing phenological phases. Furthermore, the climatic conditions during the 2024 cultivation seasons were highly variable during all the months. The highest precipitation was during the May period, which was significantly higher compared to the 2022 and 2023 growing seasons with a total higher average of 57.5% and 23.5%, respectively.

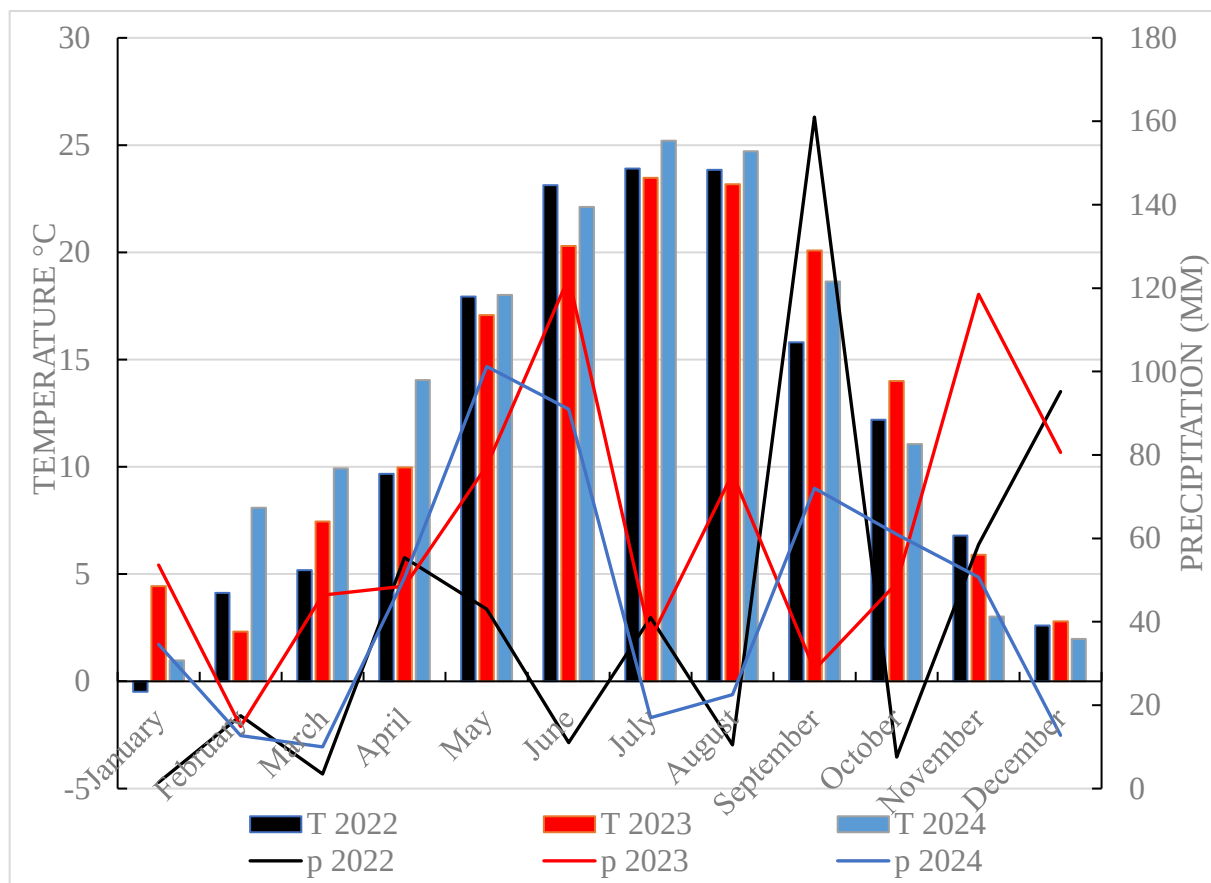


Figure 5: The monthly sum of precipitation and monthly mean of temperature during cultivation period for spring oats (Debrecen, 2022-2024).

The Pálfaí Drought Index (PaDI) was calculated to measure the water scarcity of the cultivation years for our experiment. Based on the Pálfaí and Herceg (2012) the PaDi index is measured following these steps:

$$PaDI_0 = \frac{\frac{\left[\sum_{i=apr}^{aug} T_i\right]}{5} * 100}{c + \sum_{i=oct}^{sept} (P_i * w_i)}$$

- **PaDI₀** represent the base drought index, which it is expressed in (°C 100 mm⁻¹).
- **T_i** represent the average monthly temperature for five months in a row April to August (°C).
- **P_i** refers to the total monthly precipitation measured from October to September (mm).
- **w_i** represent monthly weighting factor to calculate the PaDi index. The **w_i** values are as followed for calculated months: 0.1 for October; 0.4 for November – December; 0.5 for January – April; 0.8 for May; 1.2 for June; 1.6 for July; 0.9 for August and 0.1 for September.
- **c** present a constant value which is equal to 10 mm.

The drought index corrections factors (**k₁**, **k₂**, **k₃**) it is calculated as it is presented bellow:

- a) **k₁** represent temperature correction factor

$$k_1 = \frac{(T_{jun} + T_{jul} + T_{aug})/3}{(\bar{T}_{jun} + \bar{T}_{jul} + \bar{T}_{aug})/3}$$

- **T_{jun} + T_{jul} + T_{aug}** presenting annual temperature average for the June-August (°C).
- **$\bar{T}_{jun}, \bar{T}_{jul}, \bar{T}_{aug}$** referring to 30 years average temperature (1991-2020) for June-August for period in (°C).

- b) **k₂** represents correction factor for precipitation

$$k_2 = \sqrt[4]{\frac{2 * \bar{P}_{summer}^{min}}{MIN(P_{jun}, P_{jul}, P_{aug}) + \bar{P}_{summer}^{min}}}$$

- **$\bar{P}_{summer}^{min}$** referring to the lowest value from 30-years (1991-2020) precipitation sum of three summer months (June, July, August) in (mm).

- $MIN(P_{jun}, P_{jul}, P_{aug})$ representing the lowest value from annual precipitation sum of three summer months (June, July, August) in (mm).
- c) k_3 refereing the correction factor, for the precipitation circumstances of the previous period

$$k_3 = \sqrt[n]{\frac{\bar{P}}{\bar{P}_{36m}}}$$

- n present reduction factor, 3.0 on the plain area, on hilly or higher territories is 5.0 value.
- $\bar{P}$ refering to mean of multi-annual precipitation sum for period October-September in (mm).
- $\bar{P}_{36m}$ presenting mean precipitation sum for period October-September for previous three years in (mm).

$$\bar{P}_{36m} = \sum_{i=(year-3)Oct}^{(year)Sept} P_i / 36$$

- P_i refering to monthly precipitation sum in (mm).

PaDi index calculation in ($^{\circ}C \ 100 \ mm^{-1}$)

$$PaDI = PaDI_0 * k_1 * k_2 * k_3$$

3.3 Evaluation of the Drought Severity in the Experimental Years Based on Pálfai Drought Index

Pálfai drought index (PaDI) shows a numerical value during the growing seasons, which is a key indicator for the drought evaluation. For its calculation, hydrological years from October to September have been used, specifically the total monthly precipitation and temperature during the growing seasons. Drought evaluation involves many parameters, and for the best interpretation, the total precipitation of the experimental year and the previous three years are taken into consideration as a correction factor for the drought severity determination. PaDi index values (Table 2) show the drought intensity based on the monthly mean precipitation intensity during the experimental years. From Tables 2 and 3 we can determine

the drought intensity. Based on the Pálfai Drought Index from the experimental seasons the year 2022, was identified a serious drought year, followed by the year 2024 as a moderate drought condition, while the season 2023 was characterized by mild drought conditions.

Table 2: PaDi index calculated data for the three cultivation years in Debrecen Hungary (2022-2024).

Year	$P_{36 \text{ months}}$ (mm)	Monthly Average P for Previous 36 Months (mm)	Sum of Precipitation April-August (mm)	MIN ($P_{\text{jun}}, P_{\text{jul}}, P_{\text{aug}}$) (mm)	PaDI_0 ($^{\circ}\text{C } 100 \text{ mm}^{-1}$)	PaDI ($^{\circ}\text{C } 100 \text{ mm}^{-1}$)
2022	1519.7	42.2	160.9	10.5	8.75	11.6
2023	1567.3	43.5	359.8	35.9	3.76	4.3
2024	1761.7	48.9	282.2	17.0	5.19	6.5

Note: $P_{36 \text{ months}}$ - precipitation sum for period October-September for previous 36 months; $\text{MIN}(P_{\text{jun}}, P_{\text{jul}}, P_{\text{aug}})$ - the lowest precipitation from the sum of summer months: June, July, August.

Table 3: Classification of the drought intensity based on Pálfai Drought Index (Pálfai and Herceg, 2012)

PaDI $^{\circ}\text{C } 100 \text{ mm}^{-1}$	Drought Classification
<4	Droughtless
4-6	Mild
6-8	Moderate
8-10	Medium
10-15	Serious
15-30	Very serious
>30	Extreme

3.4 The design and treatment of the spring oat experiment

The spring oat field experiment was established on small plots measuring 3x4 m (12 m²), using a randomized complete block design (RBCD) (Figure 6). Eight varieties were sown in 3 m wide adjacent strips. Four treatments were arranged within four consecutive blocks, each

containing three replications. The experiment has eight varieties, four treatments and three replications in total 96 plots. To maintain crop rotation, the experimental site within the Experimental Garden was relocated each year. The forecrops were wheat (2022), bean (2023) and soybean (2024). The number of seeds were 550 seeds for square meter, and they were sowed in five centimeters depths in 18th March 2022, 7th March 2023 and 6th March 2024. NPK nutrients were applied as follows: N₅P₁₀K₃₀ kg ha⁻¹ in October 2021 and N₅₅ kg ha⁻¹ in March 2022; N₅₅ kg ha⁻¹ in March 2023; 2024). In the 2023 season, lodging occurred in some parts of our experiment due to favorable soil nutrient supply and optimal environmental conditions, including adequate water availability and legume preceding crops.

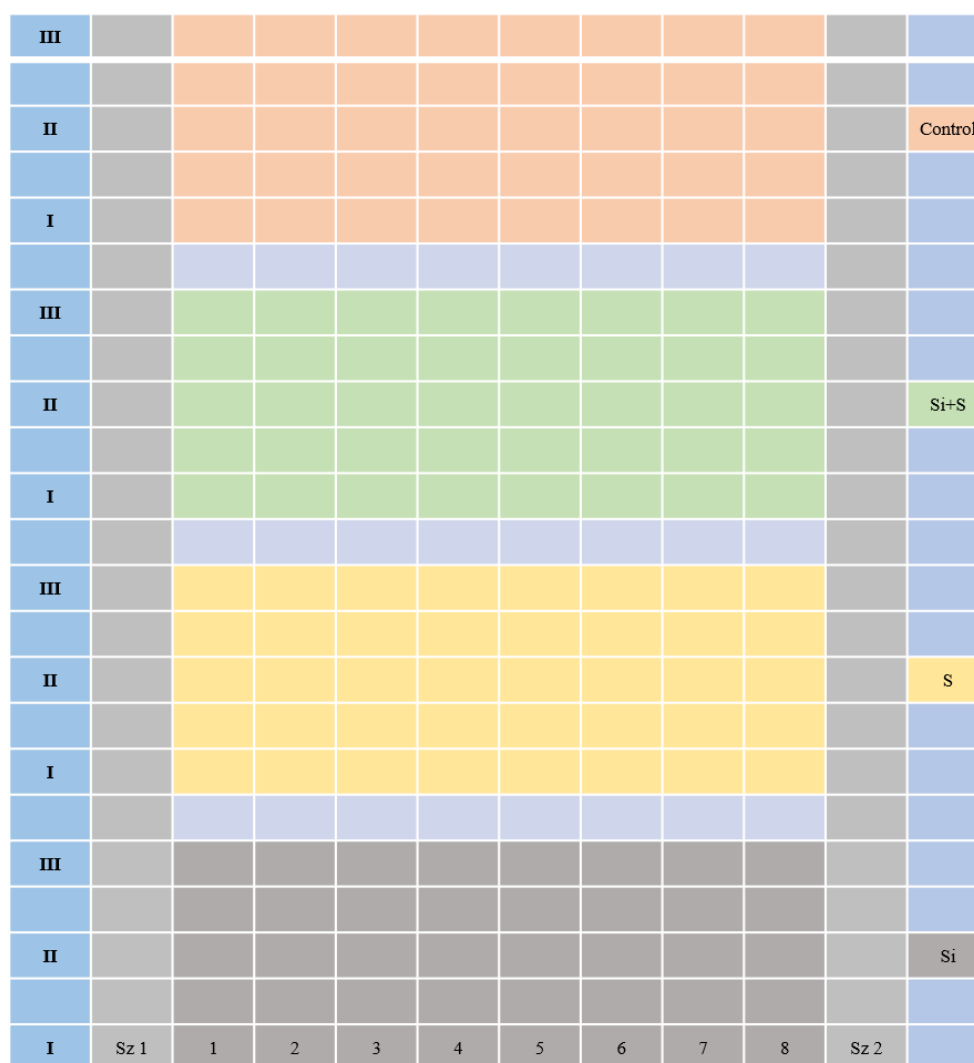


Figure 6: Schematic representation of the experimental map
Note: Sz 1=margin 1, Sz2=margin 2

The analyzed spring oat (*Avena sativa* L) varieties were selected Hungarian varieties with promising productibility: Mv Kengyel, Lota, Mv Ménes, Panna, Mv Pehely, GK Kormorán, Mv Szellő, GK Pillangó.

The foliar treatments were in four blocks, where the first one was control (without fertilizer), the second block consisted of silicon foliar fertilization 0.5 L ha^{-1} , the third block was a sulfur fertilization 0.5 L ha^{-1} , and the fourth block was a combined silicon plus sulfur application $0.5 + 5.0 \text{ L ha}^{-1}$. The foliar nutrient applications were at the 300 L ha^{-1} spraying volume and the foliar chemical compositions were:

- Sulfur: Jello Fluid commercial name with a chemical composition of high sulfur content in the lignosulfonate formulation $1000 \text{ g L}^{-1} \text{ SO}_3$, $30 \text{ g L}^{-1} \text{ N}$, $30 \text{ g L}^{-1} \text{ MgO}$, $27 \text{ g L}^{-1} \text{ B}$, $0.003 \text{ g L}^{-1} \text{ Mo}$
- Silicon: Optysil commercial name with a chemical composition of high content of silicon $200 \text{ g SiO}_2 \text{ L}^{-1}$.

With the foliar treatments were used a nonionic adjuvant containing 60% dioctyl-sulfosuccinate sodium salt at a concentration of 0.025%.

The spring oats were treated in three different phenological phases BBCH13 – three leaves unfolded, BBCH39 – flag leaf and BBCH73 – early milk phenological stages.

The plant protection was applied uniformly throughout the experiment. For the seed dressing tebuconazole was used, and for the pest control we applied lambda cyhalothrin in the amount of 150 mL ha^{-1} at the end of tillering and end of flowering phases (BBCH29 and BBCH69). The pest control was specifically against the *Oulema melanopus* (spring oat leaf beetle).

3.5 Field measurements and data collection

Leaf area index (LAI) and normalized difference vegetative index (NDVI) data were collected from the selected spring oat leaves. Leaf area index (LAI) was determined using a LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE, USA) operated in single-sensor mode, with both above- and below-canopy measurements taken using the same LAI-2050 optical sensor. For each plot, two above-canopy and eight below-canopy readings were

recorded. The eight below-canopy measurements were averaged to obtain a representative LAI value for each plot.

Normalized difference vegetation index (NDVI) was measured in the field using a hand-held Trimble Inc. GreenSeeker crop sensor. The sensor provides active illumination through light-emitting diodes (LEDs) at wavelengths of 656 nm and 774 nm. This two-band optical reflectance sensor records the intensity of reflected red and near-infrared (NIR) radiation to calculate the optical reflectance ratio. Measurements were initiated by pulling the trigger at the beginning of each plot, and multiple readings were collected across the sensing area. An average NDVI value was automatically calculated when the trigger was released at the end of the row. During measurements, the sensor was held at a constant height of 60 cm above the canopy to ensure reliable readings.

NDVI and LAI measurements were performed weekly, beginning at the BBCH 13 phenological stage and continuing until the end of the growing season. Seven measurements were carried out during the growing season in 2022 and 2023, while eight measurements were taken in 2024.

The photosynthetic total conductance, transpiration, and assimilation rate were measured on intact leaves using a LI-6800 portable photosynthesis system (LI-COR, Lincoln, NE, USA). The instrument is equipped with two high-precision infrared gas analyzers that determine the mole fractions of CO₂ and H₂O in the air. Based on the inlet and outlet concentrations of CO₂ ($\mu\text{mol mol}^{-1}$) and H₂O (mmol mol^{-1}), together with leaf temperature ($^{\circ}\text{C}$), atmospheric pressure (kPa), air flow rate ($\mu\text{mol s}^{-1}$), and other recorded variables, the system calculates net photosynthetic rate, transpiration rate, total conductance and other physiological parameters. Photosynthetically active radiation in the chamber was maintained at $1500 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$, with a spectral composition of 90% red light (625 nm) and 10% blue light (475 nm). The chamber CO₂ concentration was maintained at $400 \mu\text{mol mol}^{-1}$. Measurements were performed on light-adapted leaves, with six readings taken per leaf on two plants from each plot. Data were recorded after stabilization of the measured parameters, but not earlier than 120 s after chamber closure. Photosynthetic parameters were measured at two-week intervals, starting in early May. During the growing season, two measurements were conducted in 2022, whereas three measurements were performed in both 2023 and 2024.

The harvesting was completed by using a Wintersteiger 125 plot combine with a 125 cm cutting width. The harvesting time was performed on the 11th July 2024, and 2022 and 24th July 2023. Grain samples were taken from each harvested plot to determine grain moisture content, thousand kernels weight and grain quality parameters.

3.6. The grain element content analytical method

The grain quality analysis for the measurement of the elemental composition has been conducted first through the grinding of the spring oat grain samples, and then through the predigestion and digestion using a wet acid digestion preparation sample. One gram sample of the spring oat grains was transferred into the tubes for the digestion, and 10 mL of nitric acid was added (HNO₃, 69% v/v) (VWR International Ltd., Radnor, PA, USA). The reaction time for the predigestion phase required twelve hours, which was followed by heating at temperature of 60 °C for 30 minutes using a LA-BOR MIM OE-718/A block digestion system. Then the samples have been cooling, and 3 cm³ of hydrogen peroxide were added to each sample (H₂O₂, 30 % v/v) (VWR International Ltd., Radnor, PA, USA).

The temperature in the digestion phase was 120 °C for 90 minutes for the mineralization of the organic material. The final digestion solution volume was adjusted to 50 cm³ using ultrapure water (Milli-Q two-level water purification system, Millipore S.A.S, Molsheim, France). Filtrak 388 filter paper was used for the filtration of the digested solution and for the final elemental analysis with Inductively Coupled Plasma Optical Emission Spectrometer - ICP-OES. PerkinElmer Optima 3300 DV ICP-OES was used for the quantification of all analyzed elements. The ICP-OES instrument has a high precision for multi element content detection. Hungarian standard methods (MSZ and SVM) were used for the determination of the spring oat grain element content, with an analytical deviation allowance of ± 10 % for repeatability and precision acceptance.

3.7 Data Analysis

GenStat Program 18th version was used for the statistical analysis, where all of the data were subjected to this statistical program. ANOVA analysis with a two factors design was performed for the statistics of the treatments and for average value comparison. Furthermore, the variety and treatment interaction were determined. For the variance analysis,

homogeneity and normality tests were performed. In addition, the treatment variety and year interaction factor were performed for the three factors variance analysis. The average values of the spring oat grains for treatment variety and year interaction were compared by using the LSD (least significant difference) with a 5% level of probability. The year analysis was performed separately for each year. The Pearson correlation was performed for the linear correlation. PCA (principal component analysis). R statistics was used for the treatment differences of the nutrient element content of spring oat grain (R Core Team., 2025). The major of the original variance and correlated variables are shown in the orthogonal principal components during the principal components analysis, where a highlighted cluster is shown for the differences of the elemental spring grain content.

4. RESULTS AND DISCUSSION

4.1 Effect of Silicon and Sulfur Foliar Treatments and Genotypes on the Leaf Area Index and Normalized Difference Vegetation Index in Spring Oat

4.1.1 Leaf Area Index Dynamics in Response to Silicon and Sulfur Foliar Treatments and Genotypes at Different BBCH Spring Oat Phenological Phases

The data measured for the leaf area index are presented in seven phenological stages during the 2022 (BBCH13, BBCH30, BBCH39, BBCH51, BBCH73, BBCH77 and BBCH83) cultivation year. Furthermore, in the 2023 cultivation year, all the phenological phases from 2022 were measured, and also BBCH22 was added instead of BBCH30. In addition, even the 2024 growing seasons are characterized by the leaf area measurement from all the phenological stages (BBCH) measured during 2023, except the BBCH51. The impact of foliar nutrient application on the increase of leaf area index is highly dependent on the type of element, applied dosage, phenological stage, variety, and environmental conditions. In our experiment, different results during the vegetative seasons are presented based on foliar application in three phenological stages (*BBCH13, *BBCH39, and *BBCH73) and three seasons.

The serious drought year (2022) is challenging year in environmental conditions with no significance differences between treatments ($p > 0.05$) for the leaf area index measurements at three phenological stages, BBCH13, BBCH51, and BBCH77. However, at the BBCH30 and BBCH83 between foliar treatments, there were significant differences ($p < 0.05$), and the leaf area index showed the highest values on the control treatments, while silicon and sulfur applications were in the lowest mean value, 4.828 and 3.259, respectively.

The mild drought year (2023) showed a variable leaf area index between phenological stages in five stages (BBCH13, BBCH22, BBCH73, BBCH77, and BBCH83) and there were no significant differences ($p > 0.05$) between treatments. Phenological stages BBCH39 and BBCH51 are characterized by significant differences ($p < 0.05$), while at the beginning of heading, the silicon foliar treatments resulted in the highest leaf area index.

Leaf area index (LAI) values in different treatments and measured in six phenological stages in the moderated drought year (2024) resulted in no significant differences ($p > 0.05$) in the BBCH13, BBCH39, BBCH73, and BBCH83 phases. However, the phenological growing stages BBCH22 and BBCH30 are characterized by significant differences ($p < 0.05$) between treatments, where the control showed the highest leaf area index with a value of 3.372 and 4.482, respectively. (Figure 7)

In all the cultivation seasons of the experimental years (2022-2024), LAI were relatively low in the three leaves unfolded stage (BBCH13) compared to other measured phenological phases in spring oats. LAI index reached the maximum during the serious drought conditions at the BBCH30 phase, while in the same environmental conditions at the BBCH83, its value dropped immediately. However, during the mild and moderate drought conditions (2023 and 2024) the LAI values remained very high at the early dough phase (BBCH83) compared to serious drought conditions year (2022), where the highest difference index was 1.22 and 1.125 at the sulfur application. The treatment effect on foliar resulted twelve times in total during the period of growing of spring oats, where there was no significant difference ($p > 0.05$), in accordance with the Wadas and Kondraciuk (2025).



Figure 7: Leaf area index response in spring oat under C, S, Si, Si+S foliar treatments, during different phenological growth stages (BBCH) (Debrecen, 2022 – 2024).

*Note: Clustered columns show average values across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within analyzed BBCH growing stage, determined by LSD at $p \leq 0.05$ significance level. * treatment period.*

The Leaf Area Index is presented in Figure 8 measured in eight different phenological stages (BBCH13, BBCH22, BBCH30, BBCH39, BBCH51, BBCH73, BBCH77, and BBCH83) and in eight spring oat varieties during three growing years (2022-2024). The statistic resulted in significant differences ($p < 0.05$) at the phenological phases, environmental conditions, and varietal divergences, reflecting the different adaption capacity of the studied spring oat varieties.

In the serious drought year (2022), LAI ranges lower compared to other cultivation years in all BBCH stages. In the three leaves unfolded (BBCH13) stage, LAI values ranged from 3.341 (Mv Pehely) to 4.571 (Mv Szellő) with obvious differences between varieties, suggesting that during this phase, the values of the canopy were limited by drought stress availability. Furthermore, in the serious drought year, the Lota genotype showed the significantly lowest LAI index at four different phenological stages (BBCH39, BBCH51, BBCH73, and BBCH77), with an annual mean ranging from 3.7 – 4.2. In addition, the lowest values were found at the BBCH83 phase with no significant differences between Lota (3.15), Panna (3.17), and GK Kormorán (3.42). Furthermore, the lower leaf area index is a strong indicator of water use availability and a sensitive respond to drought conditions (Noor et al., 2024). However, the Mv Ménes genotype showed significantly higher stability overall varieties with the highest leaf area index at four different phenological phases, BBCH39 (5.02), BBCH51 (5.04), BBCH73 (5.02), and BBCH77 (4.74), indicating a strong adaptive ability under serious drought conditions and a high potential for water use efficiency.

The year 2023 is defined as a mild drought year, where the variety Mv Kengyel reached the highest LAI value during the BBCH73 stage (5.427) compared to all cultivated years and studied varieties. Furthermore, the highest LAI value observed for all the studied spring oat varieties during the BBCH73 stage as a physiological parameter stimulated the canopy development, promoting the efficiency of water use and spring oat crop development, where the plant maintained the leaf area, which resulting in an increase in the LAI values. In contrast, a serious drought environmental year because of the limit water use efficiency the cell turgor and leaf development are inhibited by environmental factors. However, the Mv Pehely variety had a regulated canopy development values, where its highest maximum value in each cultivated seasons were 4.461 (2022), 4.453 (2023), and 4.786 (2024), showing the

ability to maintain stable leaf area index and development, reflecting a genetic importance in the control of leaf expansion.

The early dough stages (BBCH83) resulted in significantly ($p < 0.05$) lower values during the serious drought season (2022) compared to mild and moderate seasons (2023 and 2024). The LAI decline values during a serious drought year at the early dough stage indicate a water limitation during the grain filling, leading to a reduction in leaf water potential. In contrast, under a mild drought season (2023), the LAI values during the mild dough stage (BBCH83) were constant to the early milk (BBCH73), indicating a sufficient water availability and metabolic activity in the leaf hydration sustainability, which allowed the expansion of the leaf area by resulting in higher LAI values.

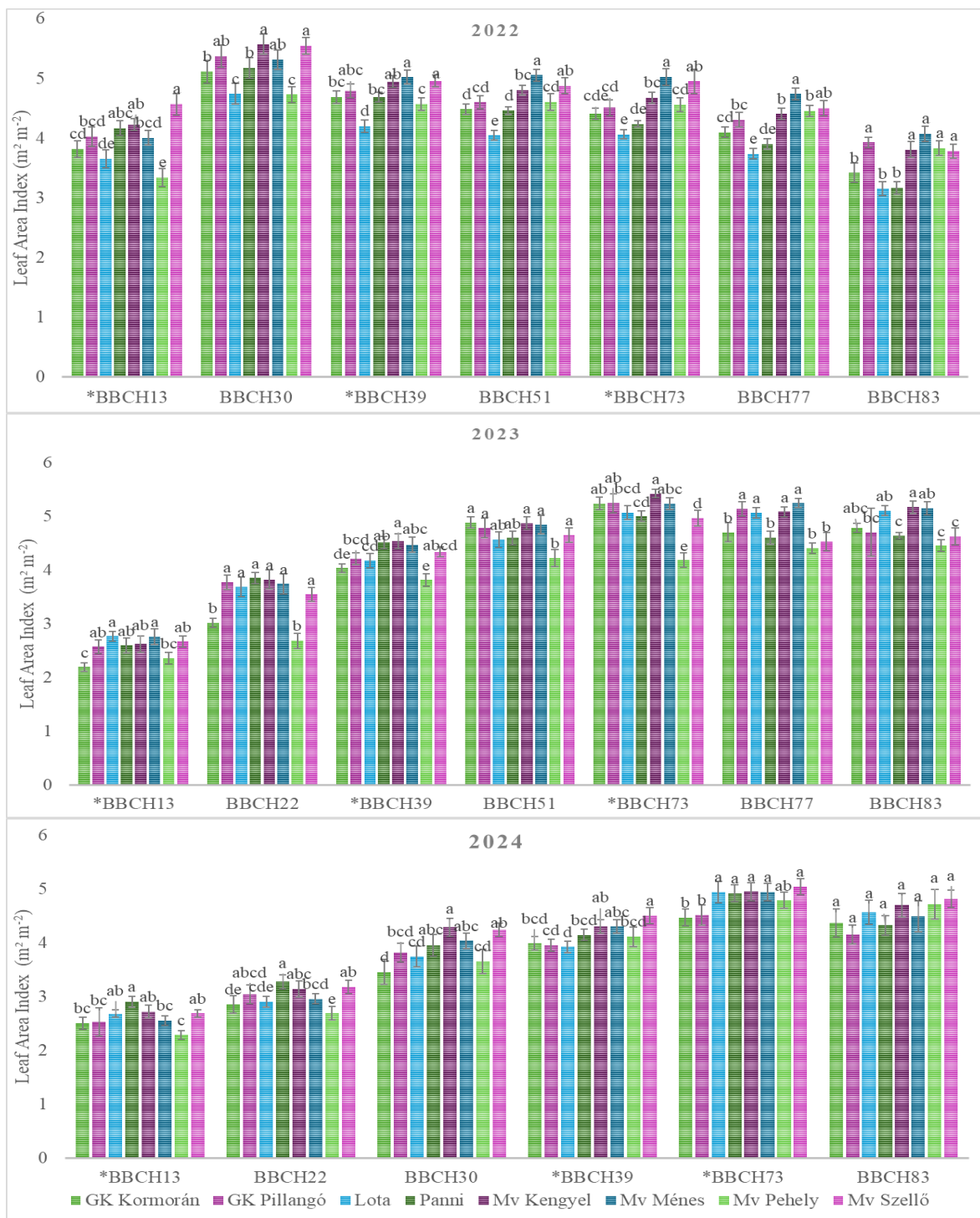


Figure 8: Leaf area index response in spring oat varieties, during different phenological growth stages (BBCH) (Debrecen, 2022-2024).

Note: Clustered columns show averages values across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within analyzed BBCH growing stage, determined by LSD at $p \leq 0.05$ significance level. * treatment period.

4.1.2 Normalized Difference Vegetation Index Dynamics in Response to Silicon and Sulfur Foliar Treatments and Genotypes at Different BBCH Spring Oat Phenological Phases

The Normalized Difference Vegetation Index it shows the canopy greenness of spring oats under the foliar treatment of silicon, sulfur and a combination of silicon and sulfur over the three consecutive growing years (2022-2024) at eight main physiological growing phases of three leaves unfolded (BBCH13), two tillers detectable (BBCH22), beginning of stem elongation (BBCH30), flag leaf stage (BBCH39), beginning of heading (BBCH51), early milk (BBCH73), late milk (BBCH77) and early dough (BBCH83). From the results it is shown that they are significantly affected by environmental drought conditions, phenological stage and foliar applications which have reflected the canopy greenness values.

During the serious drought conditions (2022), the values of NDVI were relatively high and significantly different ($p < 0.05$) in the first two measured stages (BBCH13 and BBCH30), showing a high chlorophyll content in the younger leaves and better growing seasons. However, higher NDVI values during the BBCH13 stage for the none treated part show the limited effectiveness of foliar application during this stage, and in many scenarios, the effectiveness of foliar treatments usually appears at later stages. Furthermore, there were significant differences ($p < 0.05$) even during the BBCH39, BBCH51, BBCH73, BBCH77, and BBCH83 stages with a negative impact on the treatment applications, since there was no increase in the canopy greenness. The negative impact of the treatment indicates that a serious drought environment dominated the greenness of the canopy behavior, and strongly showing a dominance of water availability on the NDVI availability compared to foliar nutrient management. In addition, the significant consistency on the negative impact of foliar treatment indicates in the early dough phase (BBCH83) during the serious drought season (2022) for the canopy greenness values reflects a water limitation factor.

In the mild drought season (2023), the canopy greenness results were significantly different in all BBCH phenological growing phases, where the environmental conditions did not dominate the expression of physiological process by showing differences in NDVI values among the treated and measured phenological stages. The positive response on the NDVI values resulted in the two tiller detectable stage, where the silicon foliar treatment resulted

in higher canopy greenness compared to all treatments. In addition, in the four phenological stages (BBCH13, BBCH39, BBCH73, and BBCH83), there were no significance difference ($p < 0.05$) between silicon and control treatment in the NDVI values. However, in the BBCH51 and BBCH77 phenological stages, the control treatment had higher canopy greenness values compared to foliar treatments, indicating a negative impact at these phenological stages and doesn't imply a better spring oat performance (Huemmrich et al., 2021).

Additionally, at the medium drought conditions (2024), significant differences ($p < 0.05$) appeared for all foliar treatments and for BBCH13, BBCH22, BBCH30, BBCH39, and BBCH51 phenological phases. However, no statistically significant differences for foliar application were observed during the BBCH71, BBCH77, and BBCH83 growing stages. (Figure 9)

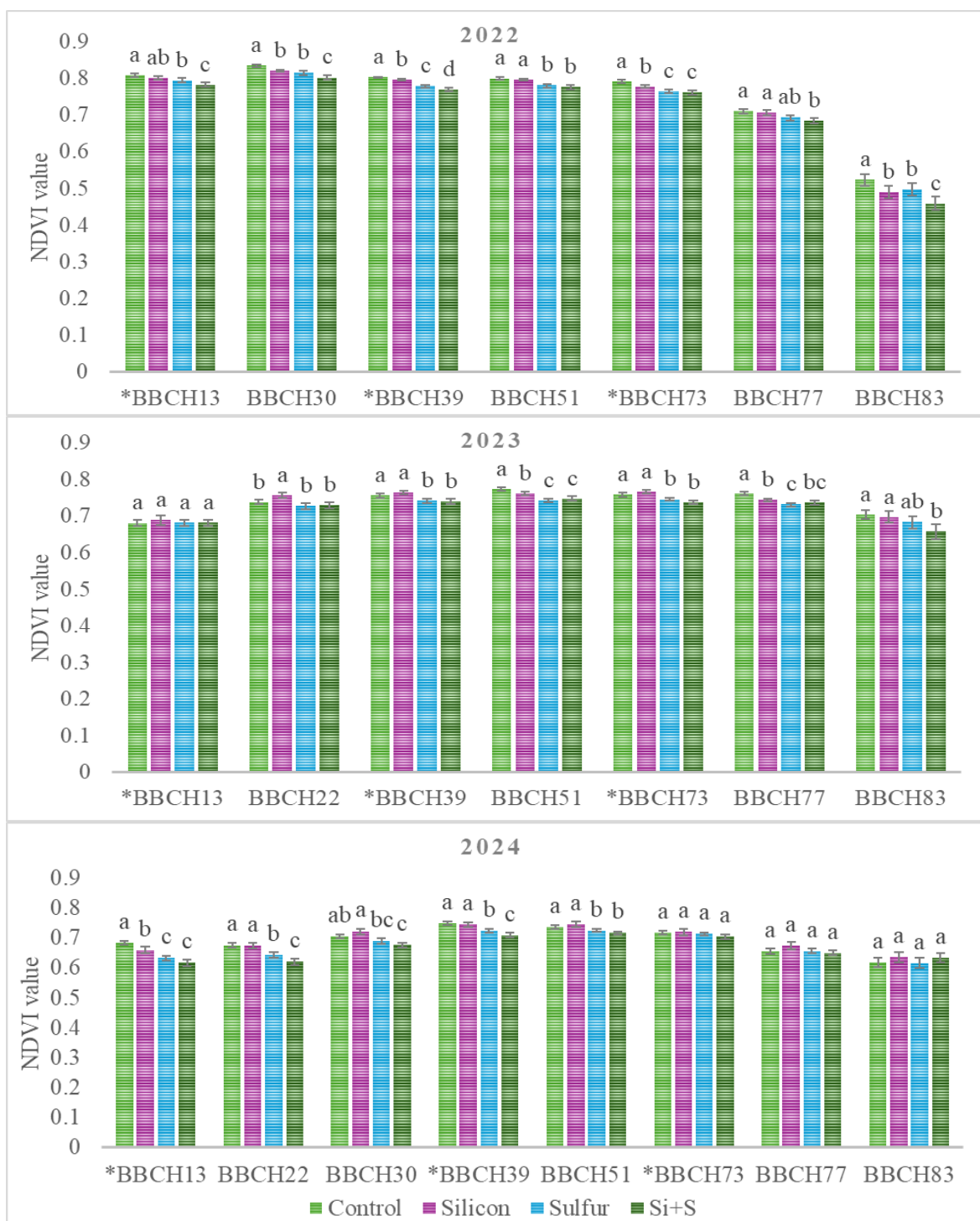


Figure 9: Normalized Difference Vegetation Index response in spring oat under C, S, Si, Si+S foliar treatments, during different phenological growth stages (BBCH) (Debrecen, 2022-2024)

*Note: Clustered columns show average values across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within analyzed BBCH growing stage, determined by LSD at $p \leq 0.05$ significance level. * treatment application time.*

The Canopy greenness Variation is presented in the Figure 10, measured in eight different phenological stages (BBCH13, BBCH22, BBCH30, BBCH39, BBCH51, BBCH73, BBCH77, and BBCH83) and in eight spring oat varieties during three growing years (2022-2024). The statistic resulted in significant differences ($p < 0.05$) at the phenological phases, environmental conditions and varietal divergences, reflecting the different adaption capacity of the studied spring oat varieties.

In the serious drought year (2022), NDVI showed a tendency to increase till the BBCH30 phenological stage, where it achieved the maximum value with the Mv Kengyel variety, with an average of 0.835. Furthermore, Mv Szellő showed significantly ($p < 0.05$) the highest canopy greenness in three phenological stages (BBCH13 0.819, BBCH51 0.801, and BBCH77 0.722), indicating a strong adaptive ability under serious drought conditions and a high potential on water use efficiency. However, the NDVI values were lower at the BBCH77 and BBCH83, indicating a limited water use and greenness canopy and serious drought conditions, where the lowest value of variety Lota 0.652, and Panna was 0.334, respectively.

The year 2023 is defined as a mild drought year, where the variety Mv Kengyel significantly ($p < 0.05$) reached the highest NDVI value during three phenological stages BBCH39 (0.78), BBCH73 (0.777), and BBCH77 (0.767) BBCH73 stage (5.427) compared to the studied varieties. Followed by Panna genotype, with significantly two highest values in BBCH13 (0.724) and BBCH22 (0.778) phenological phases. However, in a serious drought environmental year because of the limit water use efficiency, the leaf greenness is inhibited by environmental factors, where significantly ($p < 0.05$), the lowest values were reached by Mv Pehely in three different phenological phases BBCH51 (0.713), BBCH77 (0.716), and BBCH83 (0.6).

The NDVI values during the moderate drought conditions are characterized by a significant ($p < 0.05$) increase till the BBCH39 phenological stage, and from the BBCH51, canopy greenness values start to decrease till the BBCH83 phase. Mv Szellő variety showed the best performance during the moderate drought conditions (2024), where a significant ($p < 0.05$) difference resulted in the highest mean values in four phenological phases BBCH22 (0.703), BBCH39 (0.773), BBCH51 (0.768), and BBCH73 (0.753). Furthermore, during the BBCH13 phenological phase, significantly ($p < 0.05$) showed the highest value with variety Panna

compared to other varieties. In addition at the BBCH30 phenological phase, significantly ($p < 0.05$), the highest values were reached by Mv Szellő and Mv Kengyel. However, the Lota variety showed significantly ($p < 0.05$) the lowest mean in BBCH39 phenological stage with a mean of 0.681. In addition, Lota variety significantly shared the lowest mean even in four different phenological stages BBCH51, BBCH73, BBCH77, and BBCH83.

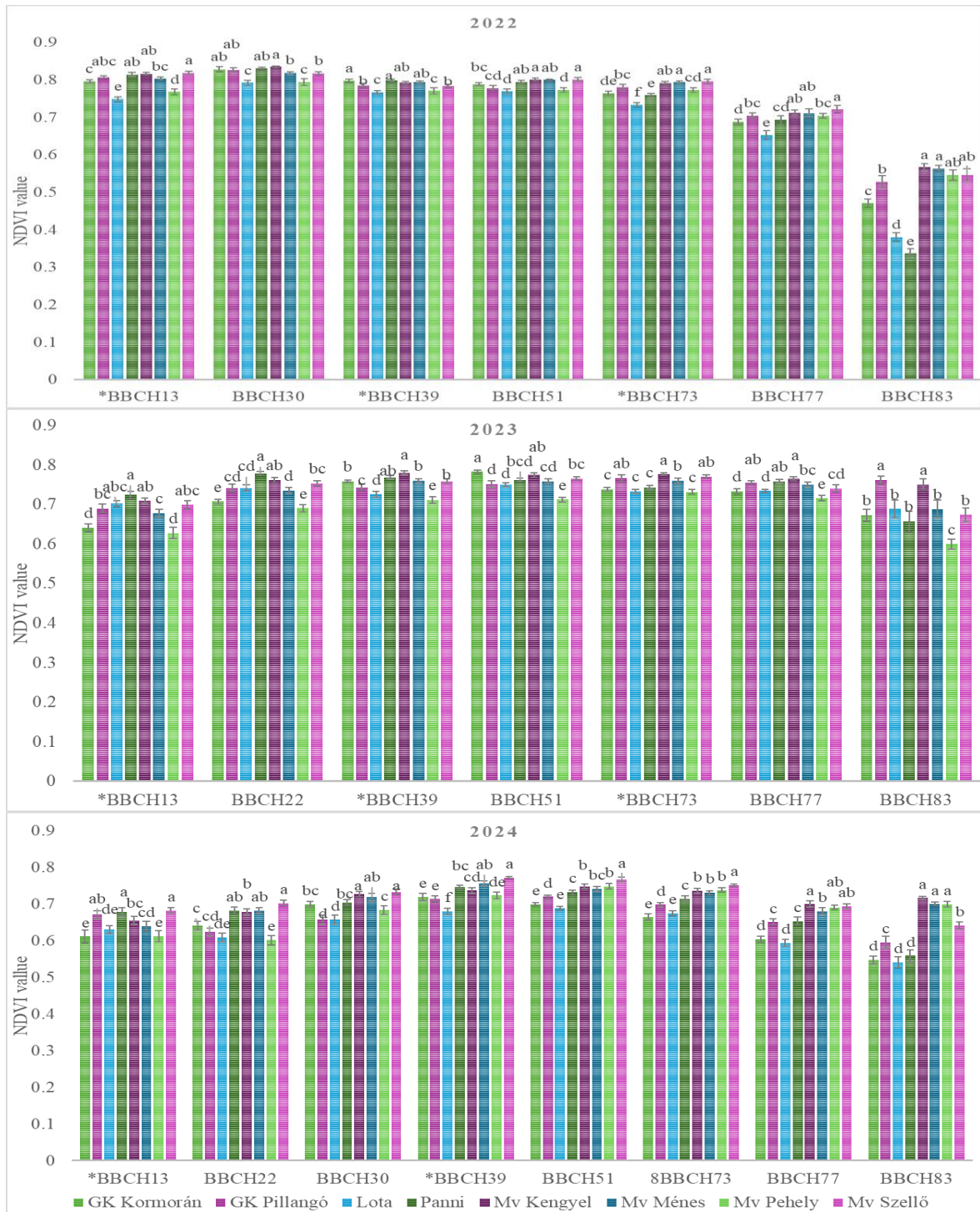


Figure 10: Normalized Difference Vegetation Index response in spring oat varieties, during different phenological growth stages (BBCH) (Debrecen, 2022-2024).

Note: Clustered columns show average values across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within analyzed BBCH growing stage, determined by LSD at $p \leq 0.05$ significance level.

**treatment application time.*

4.1.3 Correlation between Normalized Difference Vegetative Index and Leaf Area Index at Different Growth Stages

The table 4 shows the correlation coefficient between the normalized difference vegetative index (NDVI) and leaf area index (LAI) measured on different phenological phases (BBCH), giving a dynamic movement of canopy development and leaf area during the vegetative process.

The first strong positive correlation is observed at LAI results in early phenological stages BBCH13 and BBCH39 ($r = 0.83$), showing a vegetative stability development in the beginning active growing phase. However, a strong negative correlation ($r = -0.91$) is shown at the LAI BBCH13 and BBCH83, giving a strong suggestion for the phenological changes during the vegetative stage.

Table 4: Pearson correlation coefficient among leaf area index and canopy greenness variation in the experimental year of 2022-2024

	LAI				NDVI					
	BBCH 13	BBCH 39	BBCH 73	BBCH 83	BBCH 13	BBCH 39	BBCH 51	BBCH 73	BBCH 77	BBCH 83
LAI BBCH13	1.00									
LAI BBCH39	0.83	1.00								
LAI BBCH73	-0.75	-0.32	1.00							
LAI BBCH83	-0.91	-0.68	0.81	1.00						
NDVI BBCH13	0.94	0.89	-0.56	-0.77	1.00					
NDVI BBCH39	0.80	0.92	-0.29	-0.57	0.93	1.00				
NDVI BBCH51	0.79	0.90	-0.26	-0.56	0.91	0.97	1.00			
NDVI BBCH73	0.69	0.85	-0.18	-0.44	0.86	0.92	0.95	1.00		
NDVI BBCH77	-0.07	0.21	0.51	0.31	0.20	0.36	0.48	0.61	1.00	
NDVI BBCH83	-0.94	-0.66	0.86	0.94	-0.80	-0.60	-0.57	-0.43	0.37	1.00

Note: green color (positive) correlation, red color (negative) correlation and white color (no) correlation.

Regarding the NDVI correlation, a very strong is observed between three leaves unfolded and the flag leaf stage ($r = 0.93$) and the flag leaf stage with the beginning of heading ($r = 0.97$), indicating that the canopy greenness is consistent during the maximum canopy development process, by reflecting the greenness of the leaf surface in the intensive growth period.

4.2 Effect Silicon and Sulfur Foliar Treatments on the Photosynthetic Assimilation, Transpiration and Total Conductance Responses of Spring Oat Genotypes

4.2.1 Effect of Silicon and Sulfur Foliar Treatments on the Photosynthetic Assimilation Responses of Spring Oat Genotypes

4.2.1.1 Photosynthetic Assimilation Dynamics in Response to Foliar Application of Silicon and Sulfur at Different BBCH Growth Stages

The foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic assimilation at the BBCH39 and BBCH73 growing stage of studied spring oats under moderate drought seasons. The photosynthetic assimilation rate during the moderate drought conditions was significantly different ($p < 0.05$), where the results showed that control had the highest assimilation rate $21.185 \mu\text{mol m}^{-2} \text{s}^{-1}$ at flag leaf stage (BBCH39). Furthermore, during the early milk (BBCH73) phenological stage, the foliar treatment showed significant differences ($p < 0.05$) with the highest mean in control and sulfur treatment, 18.96 and $18.85 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. However, a combined treatment of silicon and sulfur and a sole treatment of silico showed the lowest assimilation response to overall treatments during the BBCH39 ($18.51 \mu\text{mol m}^{-2} \text{s}^{-1}$) and BBCH73 ($17.4 \mu\text{mol m}^{-2} \text{s}^{-1}$), respectively. (Figure 11)

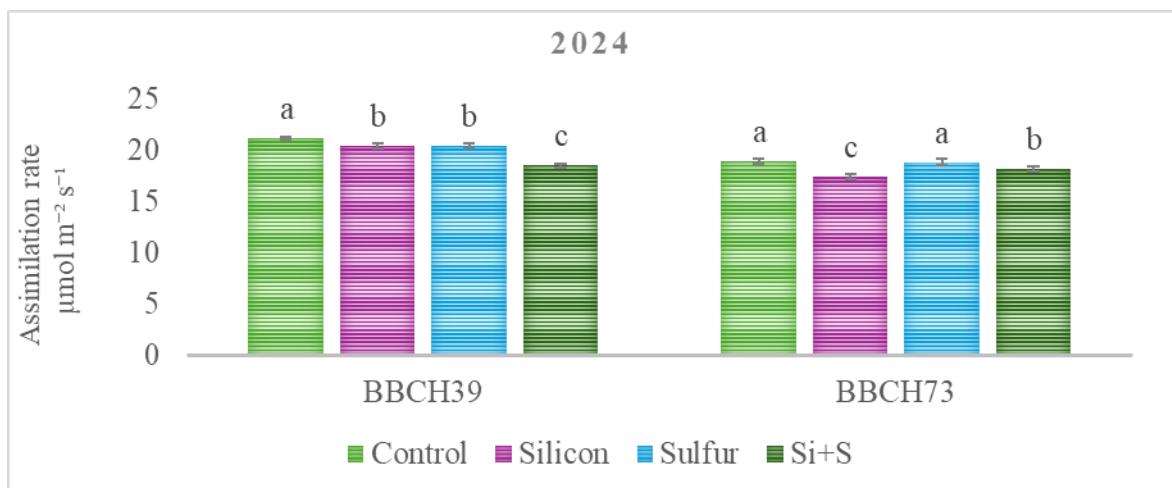


Figure 11: Photosynthetic Assimilation response in spring oat under C, S, Si, Si+S foliar treatments, flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debrecen, 2024)

Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.

The foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic assimilation at the BBCH51 and BBCH77 growing stage of studied spring oats under serious drought (2022) and mild drought (2023) environmental seasons, except for the mild drought season in the BBCH77 stage, where there were no significant differences between treatments. Foliar treatment significantly ($p < 0.05$) affected photosynthetic assimilation rate compared to control plots at serious drought conditions in the 2022 season for both BBCH51 and BBCH77 growing stages, showing a clear physiological response of the spring oats to the application of foliar nutrients through the leaves. During the serious drought conditions at the BBCH51 growing stage, the highest value was measured with Si+S foliar application ($18.46 \mu\text{mol m}^{-2} \text{s}^{-1}$), and for the BBCH77 growing stage, the highest value was measured with S foliar treatment ($9.72 \mu\text{mol m}^{-2} \text{s}^{-1}$), only $0.56 \mu\text{mol m}^{-2} \text{s}^{-1}$ higher than a combined S and Si application. Furthermore, during the serious drought conditions growing seasons, the lowest assimilation rate for each stage (BBCH51 and BBCH77), was found in the control $10.95 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $6.25 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively.

For the mild drought seasons (2023) the foliar application of S, Si and Si+S during the BBCH39 growing stage showed a significantly lower assimilation rate compared to the control, while during the BBCH73, there was no significant effect overall treatments. Overall, results prove that foliar fertilization during the BBCH51 phenological stage positively affects the rate of photosynthetic assimilation of spring oats, emphasizing the role of foliar applications of S and Si+S for spring oat physiological performance. (Figure 12)

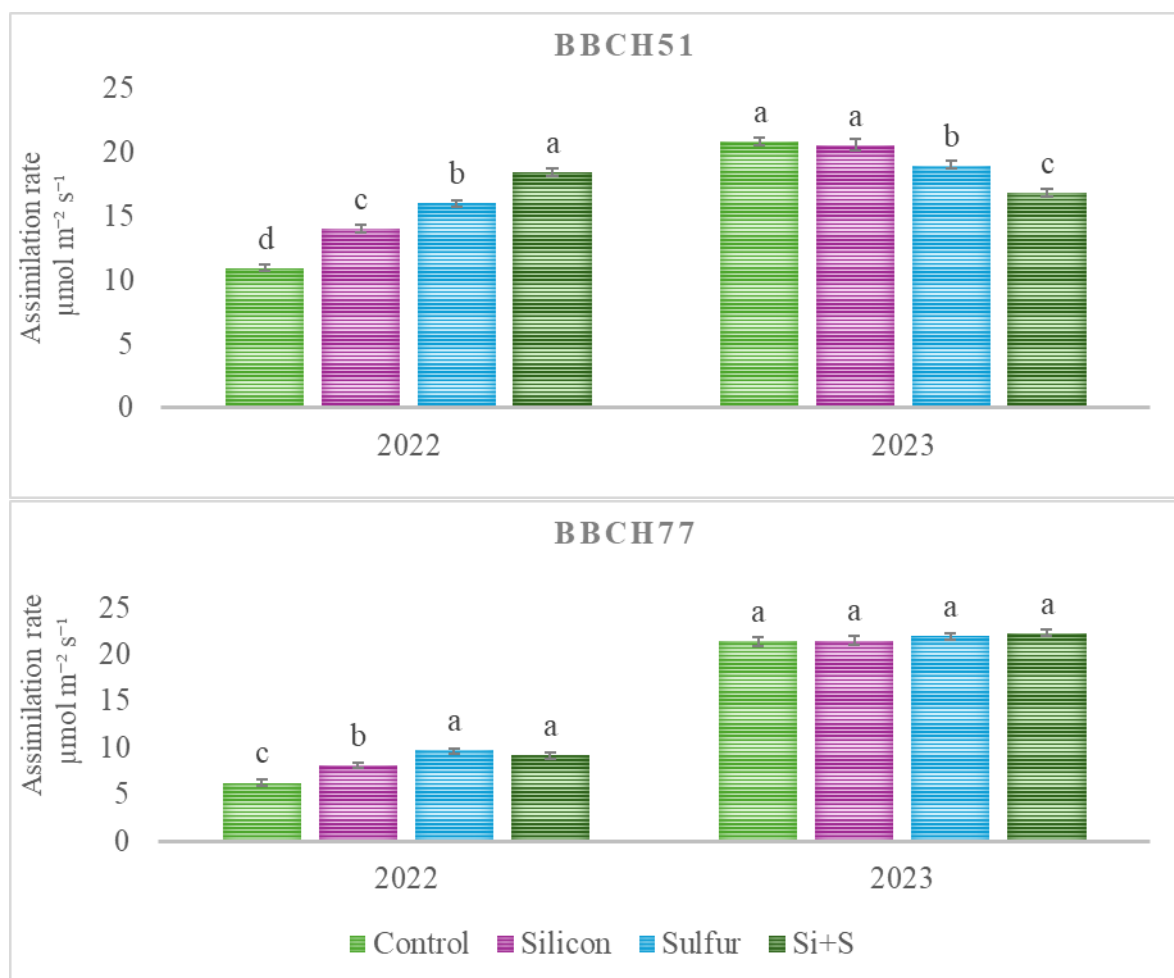


Figure 12: Photosynthetic Assimilation response in spring oat under C, S, Si, Si+S foliar treatments, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought(2022) and mild drought (2023) seasons. (Debrecen, 2022-2023)
Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same growing season, determined by LSD at $p \leq 0.05$ significance level.

4.2.1.2 Photosynthetic Assimilation Dynamics among Genotypes at Different Growth Stages

The varietal differences were statistically significant ($p < 0.05$) in the photosynthetic assimilation parameters at the BBCH39 and BBCH73 growing stages of the studied spring oats varieties under the moderate drought environmental season (2024). The figure shows the response of the photosynthetic assimilation rate to selected varieties during the BBCH39 and BBCH73 growing stages of spring oats throughout the moderate drought season compared to eight studied varieties. The highest assimilation rate was detected at variety Mv Szellő during the growing phase BBCH39 with an annual mean ($22.416 \mu\text{mol m}^{-2} \text{s}^{-1}$), followed by Lota ($21.303 \mu\text{mol m}^{-2} \text{s}^{-1}$) and GK Pillangó ($20.576 \mu\text{mol m}^{-2} \text{s}^{-1}$). Early milk stage (BBCH73) it is characterized by the dominance of Mv Pehely with a mean of $19.4 \mu\text{mol m}^{-2} \text{s}^{-1}$, followed by Panna genotype $19.04 \mu\text{mol m}^{-2} \text{s}^{-1}$, while the lowest assimilation was measured at GK Kormorán genotype $16.74 \mu\text{mol m}^{-2} \text{s}^{-1}$. The varietal response to assimilation rate showed an important factor in the different assimilation between genotypes (Figure 13).

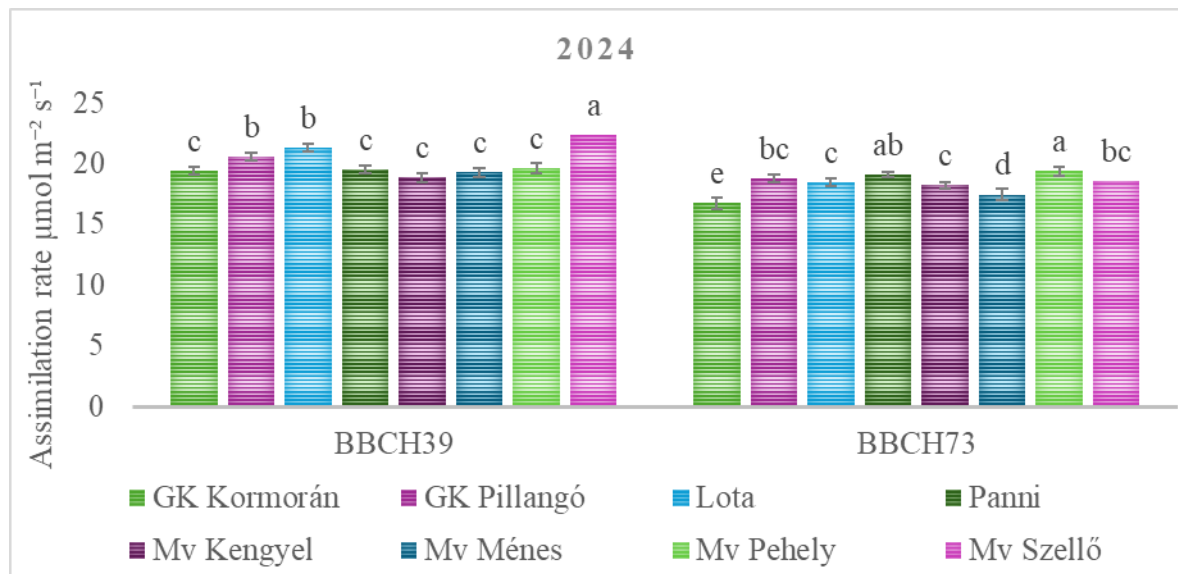


Figure 13: Photosynthetic Assimilation response in spring oat varieties, during flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debrecen, 2024). *Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.*

The results showed that varietal differences in Figure 14 were statistically significant ($p < 0.05$) in the photosynthetic assimilation parameters at the BBCH51 and BBCH77 growing stage of studied spring oats varieties under serious and mild drought environmental seasons. There were so many significant changes ($p < 0.05$) that affected photosynthetic assimilation rate detected under same growing phenological phase or different growing seasons across the analyzed varieties. The highest assimilation rate for BBCH51 and BBCH77 phenological phase was detected during the mild drought season, where variety Panna showed significantly the best performance ($p < 0.05$) for both phenological phases, with a mean of 24.29 and 24.13 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. However, Panna resulted significantly ($p < 0.05$) with the lowest assimilation rate in the BBCH77 during serious drought conditions, with an average of 6.68 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Lota variety resulted in a contrast assimilation rate, where during the serious drought year it resulted in the highest assimilation value, 16.73 $\mu\text{mol m}^{-2} \text{s}^{-1}$, compared to all varieties, while during mild drought conditions at BBCH77, it achieved the lowest assimilation value, with a mean of 19.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$ overall other genotypes. In contrast, Mv Szellő genotype during a serious drought year at the BBCH77 resulted significantly with the lowest assimilation value 7.21 $\mu\text{mol m}^{-2} \text{s}^{-1}$, while in the same phenological stage but in a mild drought year, the assimilation rate was significantly the highest 24 $\mu\text{mol m}^{-2} \text{s}^{-1}$ compared to six other varieties.

Statistically significant differences ($p < 0.05$) in the photosynthetic assimilation rate at two growing phases, BBCH51 and BBCH77, indicate the dependence of the developmental stages, varietal differences, and drought severity. The higher photosynthetic assimilation values were observed under mild drought conditions (2023), reflecting the capacity of assimilation activity, while a reduction of assimilation was observed during the serious drought conditions (2022). The observed results between seasons and growing stages highlight the varietal divergences and environmental conditions as key factors in the adaptation of spring oat under different climatic conditions.



Figure 14: Photosynthetic Assimilation response in spring oat varieties, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought (2022) and mild drought (2023) seasons. (Debrecen, 2022, 2023)

Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same growing season, determined by LSD at $p \leq 0.05$ significance level.

4.2.2 Effect of Silicon and Sulfur Foliar Treatments on the Photosynthetic Transpiration Responses of Spring Oat Genotypes

4.2.2.1 Photosynthetic Transpiration Dynamics in Response to Foliar Application of Silicon and Sulfur at Different BBCH Growth Stages

The foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic transpiration at the two phenological stages BBCH39 and BBCH73 from the studied spring oats under moderate drought seasons (2024). The photosynthetic transpiration rate during the moderate drought conditions was significantly different ($p < 0.05$), where the results showed that sulfur foliar treatment had the highest transpiration rate, $8.089 \text{ mmol m}^{-2} \text{ s}^{-1}$, at the flag leaf stage (BBCH39). Furthermore, during the early milk (BBCH73) phenological stage, the foliar treatment showed significant differences ($p < 0.05$) with the highest mean in S and Si+S treatment, 16.748 and $16.351 \text{ mmol m}^{-2} \text{ s}^{-1}$, respectively. However, a combined treatment of silicon and sulfur showed the lowest transpiration values among all treatments during the BBCH39 ($5.859 \text{ mmol m}^{-2} \text{ s}^{-1}$) and BBCH73 ($14.829 \text{ mmol m}^{-2} \text{ s}^{-1}$), respectively. (Figure 15)

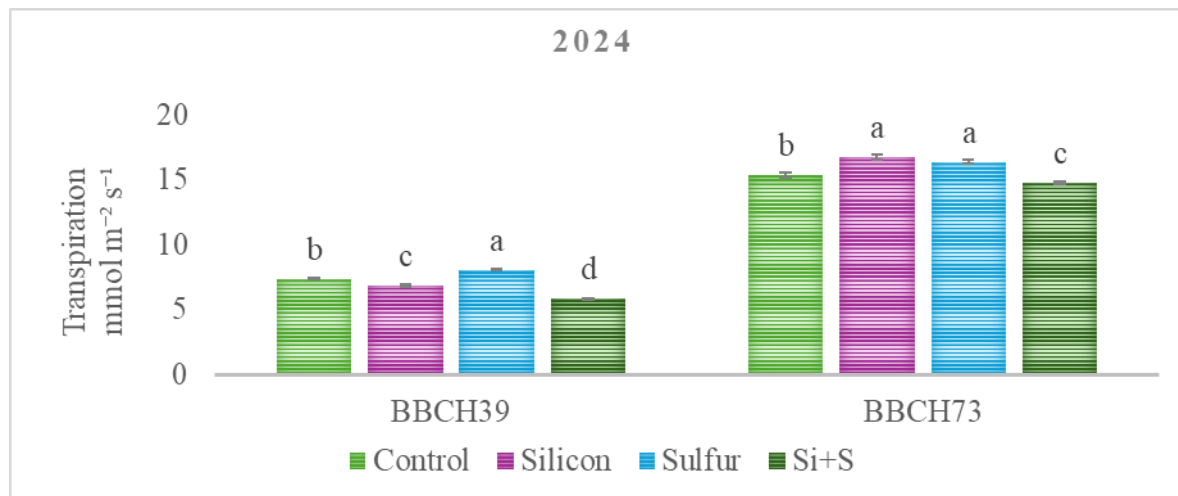


Figure 15: Photosynthetic Transpiration response in spring oat under C, S, Si, Si+S foliar treatments, during flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debrecen, 2024).

Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.

It was observed that foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic transpiration at the BBCH51 and BBCH77 growing stage of studied spring oats under serious drought (2022) and mild drought (2023) environmental seasons. Foliar treatment significantly ($p < 0.05$) affected photosynthetic transpiration rate compared to control plots at serious drought conditions in the 2022 season for both BBCH51 and BBCH77 growing stages, showing a clear physiological response of the spring oats to the application of foliar nutrients through the leaves. During the serious drought conditions at the BBCH51 growing stage, the highest value was measured with Si+S foliar application ($4.921 \text{ mmol m}^{-2} \text{ s}^{-1}$), and for the BBCH77 growing stage, the highest value was measured in S foliar treated plots ($3.367 \text{ mmol m}^{-2} \text{ s}^{-1}$). Furthermore, during the serious drought conditions growing seasons, the lowest transpiration rate for each stage (BBCH51 and BBCH77), was found in control $2.284 \text{ mmol m}^{-2} \text{ s}^{-1}$ and $1.33 \text{ mmol m}^{-2} \text{ s}^{-1}$, respectively.

For the mild drought seasons (2023) the foliar application of S and Si+S during the BBCH39 growing stage resulted in significantly the highest transpiration rate overall treatments with a mean of 9.075 and $8.914 \text{ mmol m}^{-2} \text{ s}^{-1}$, respectively. However, a sole Si treatment resulted in the lowest transpiration values with a mean $5.345 \text{ mmol m}^{-2} \text{ s}^{-1}$, in the BBCH77 phenological stage. Overall, results prove that foliar fertilization during the BBCH51 and BBCH77 phenological stages strongly affected the rate of photosynthetic transpiration of spring oats genotypes, emphasizing the role of foliar applications of S and Si+S for spring oat physiological performance (Figure 16).

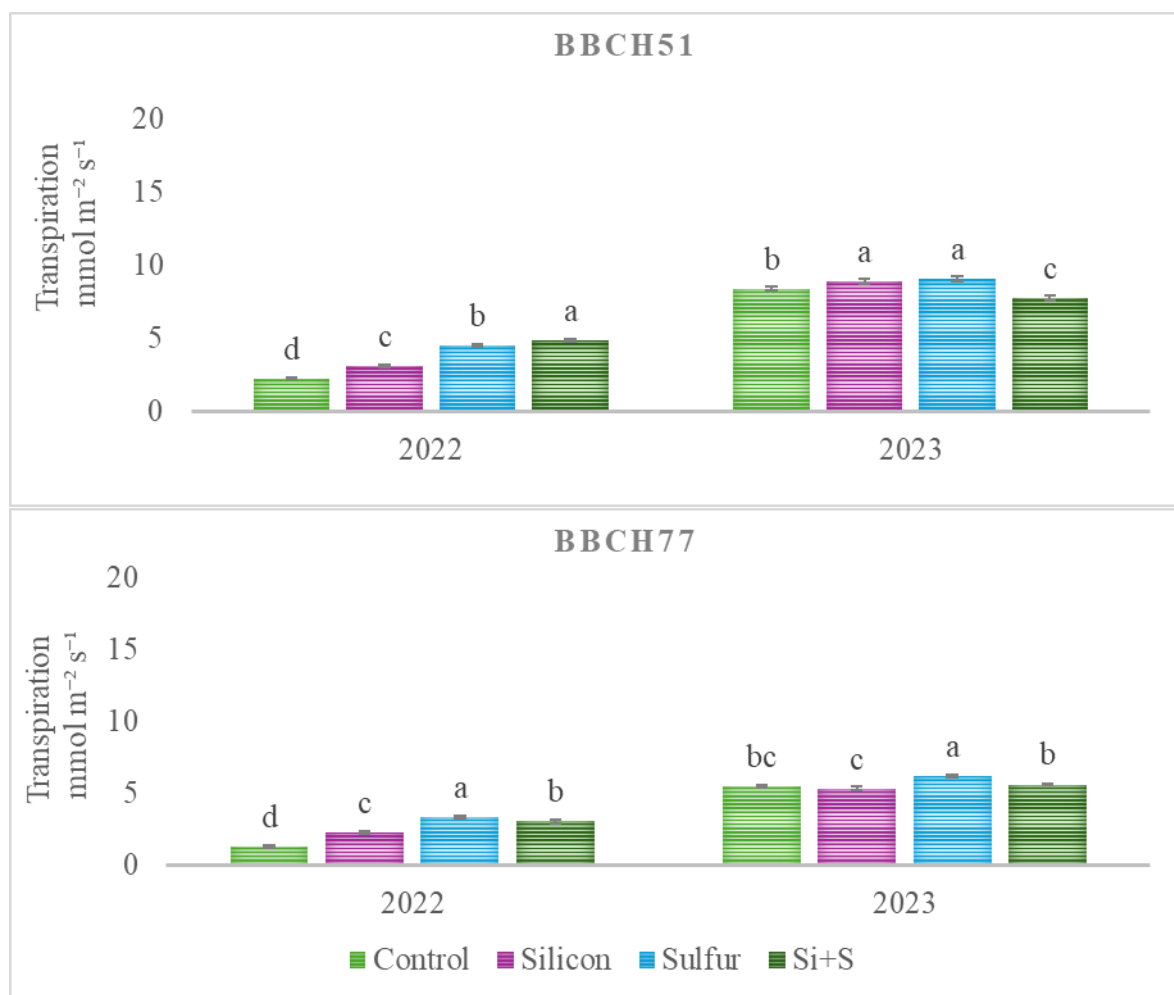


Figure 16: Photosynthetic Transpiration response in spring oat under C, S, Si, Si+S foliar treatments, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought(2022) and mild drought (2023) seasons. (Debrecen, 2022, 2023)

Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

4.2.2.2 Photosynthetic Transpiration Dynamics among Genotypes at Different Growth Stages

The varietal differences were statistically significant ($p < 0.05$) in the photosynthetic transpiration parameters at the BBCH39 and BBCH73 growing stages of the studied spring oats varieties under the moderate drought environmental season (2024). The figure shows the response of the photosynthetic transpiration rate to selected eight spring oat varieties during the BBCH39 and BBCH73 growing stage throughout the moderate drought season (2024).

The highest transpiration value was detected at variety Lota during the growing phase BBCH39 with an annual mean ($7.744 \text{ mmol m}^{-2} \text{ s}^{-1}$), while the lowest was detected by Mv Pehely genotype with a mean of ($6.56 \text{ mmol m}^{-2} \text{ s}^{-1}$). However, the early milk stage (BBCH73) it is characterized significantly ($p < 0.05$) by the dominance of Mv Pehely with a mean of $16.818 \text{ mmol m}^{-2} \text{ s}^{-1}$, while the lowest transpiration was measured at Panna $15.429 \text{ mmol m}^{-2} \text{ s}^{-1}$ and Mv Ménes $15.306 \text{ mmol m}^{-2} \text{ s}^{-1}$ genotype. (Figure 17)

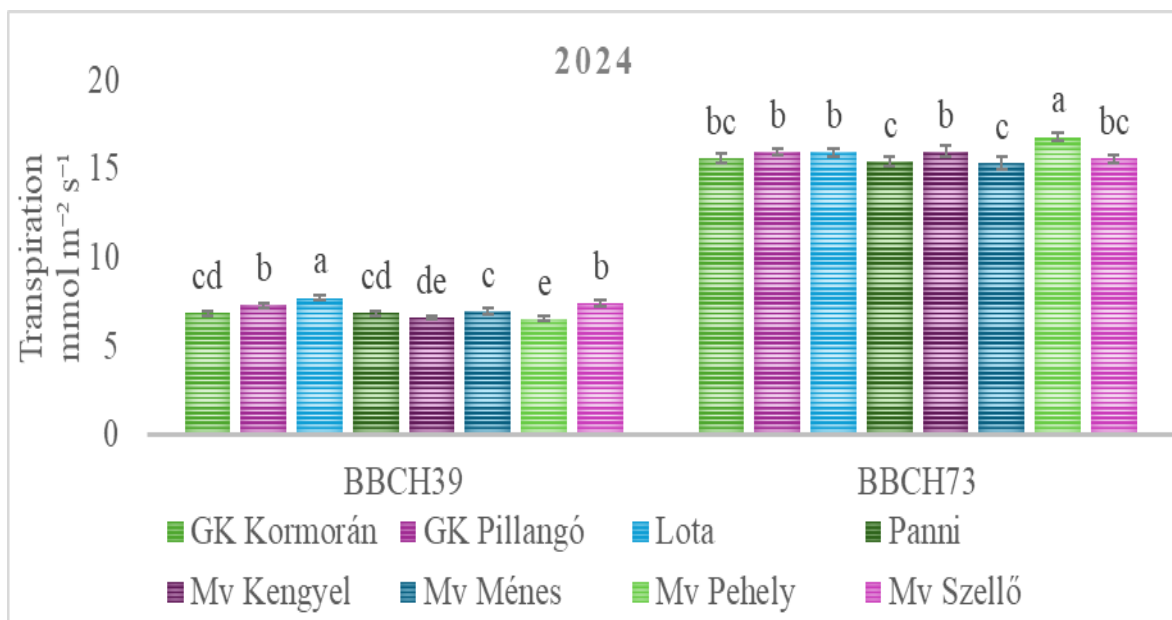


Figure 17: Photosynthetic Transpiration response in spring oat varieties, during flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debreceen, 2024). *Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.*

The results in the Figure 18 showed that varietal differences were statistically significant ($p < 0.05$) in the photosynthetic transpiration parameters at the BBCH51 and BBCH77 growing stage of studied spring oats varieties under serious and mild drought environmental seasons. There were so many significant changes ($p < 0.05$) that affected photosynthetic transpiration rate detected under same growing phenological phase or different growing seasons across the analyzed varieties. The highest transpiration rate for the beginning of heading (BBCH51) phenological phase was detected at mild drought season, where variety Panna showed the best performance ($p < 0.05$) with a mean of $10.191 \text{ mmol m}^{-2} \text{ s}^{-1}$. Furthermore, the Lota genotype showed the best performance at the BBCH51 phenological stage during the serious

drought conditions with a transpiration mean of $4.438 \text{ mmol m}^{-2} \text{ s}^{-1}$. However, the lowest transpiration values for BBCH51 and for two cultivation seasons (2022 and 2023) were reached by Mv Szellő variety with a transpiration mean of 3.324 and $7.021 \text{ mmol m}^{-2} \text{ s}^{-1}$, respectively.

The late milk phenological phase (BBCH77) it is characterized by significantly ($p < 0.05$) lower transpiration values compared to the beginning of heading (BBCH51). The best performance genotypes during the BBCH77 were Mv Ménes ($3.321 \text{ mmol m}^{-2} \text{ s}^{-1}$) during serious drought conditions and Mv Pehely ($6.195 \text{ mmol m}^{-2} \text{ s}^{-1}$) during mild drought seasons. However, the lowest transpiration was found at GK Kormorán genotype during serious drought season with a mean of $2.008 \text{ mmol m}^{-2} \text{ s}^{-1}$ and GK Pillangó genotype during the mild drought season with an average of $5.037 \text{ mmol m}^{-2} \text{ s}^{-1}$.

Statistically significant differences ($p < 0.05$) in the photosynthetic transpiration rate at two growing phases, BBCH51 and BBCH77, indicate the dependence of the developmental stages, varietal differences, and drought severity. The higher photosynthetic transpiration values were observed under mild drought conditions (2023), reflecting the capacity of transpiration activity, while a significant reduction of transpiration was observed during the serious drought conditions (2022). The observed results between seasons and growing stages highlight the varietal divergences and environmental conditions as key factors in the adaptation of spring oat under different climatic conditions.

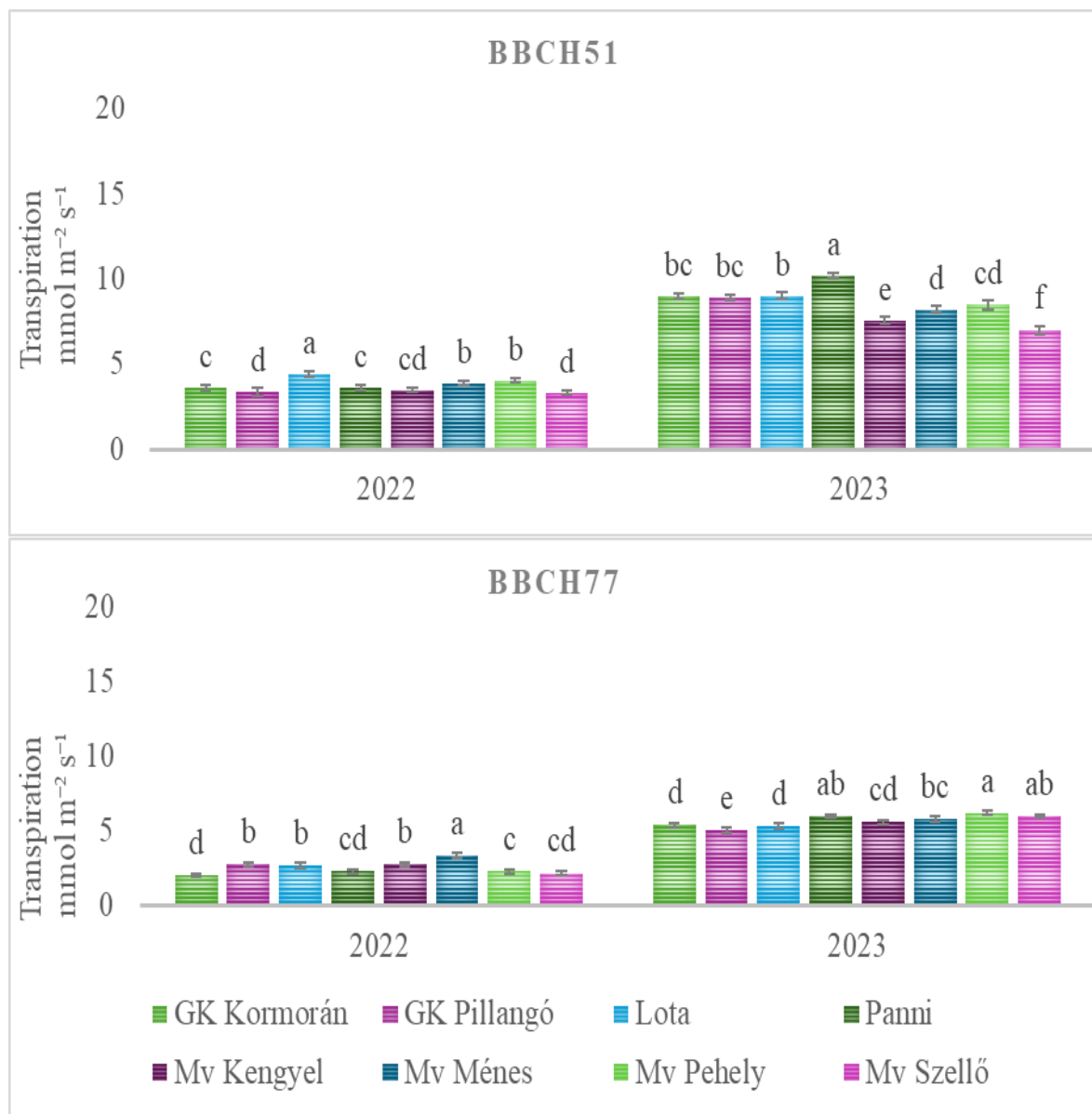


Figure 18: Photosynthetic Transpiration response in spring oat varieties, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought (2022) and mild drought (2023) seasons. (Debrecen, 2022, 2023)

Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same growing season, determined by LSD at $p \leq 0.05$ significance level.

4.2.3 Effect of Silicon and Sulfur Foliar Treatments on the Photosynthetic Total Conductance Responses of Spring Oat Genotypes

4.2.3.1 Photosynthetic Total Conductance Dynamics in Response to Foliar Application of Silicon and Sulfur at Different BBCH Growth Stages

The foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic total conductance at the BBCH39 and BBCH73 growing stage of studied spring oats under moderate drought condition. The photosynthetic total conductance during the moderate drought conditions showed significant differences ($p < 0.05$), where the highest photosynthetic total conductance rate for BBCH39 stage was in non treated parcels $0.2686 \text{ mol m}^{-2} \text{ s}^{-1}$, and for BBCH73 were Si foliar treatment, with a mean of $0.281 \text{ mol m}^{-2} \text{ s}^{-1}$. However, the lowest value during the moderate drought conditions (2024) for both growing stages for spring oats was found with a combined Si and S application with a mean value of $0.189 \text{ mol m}^{-2} \text{ s}^{-1}$ for BBCH39 and $0.242 \text{ mol m}^{-2} \text{ s}^{-1}$ for BBCH73. (Figure 19)

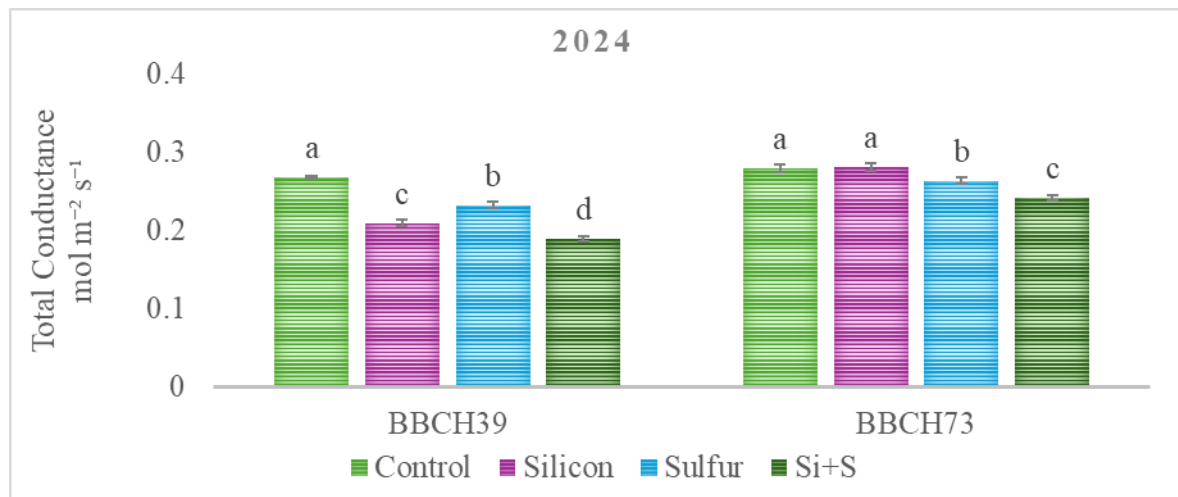


Figure 19: Photosynthetic Total Conductance response in spring oat under C, S, Si, Si+S foliar treatments, during flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debrecen, 2024).

Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.

It was observed that foliar treatments were statistically significant ($p < 0.05$) in the photosynthetic total conductance at the BBCH51 and BBCH77 growing stage of studied spring oats under serious and mild drought conditions. Foliar treatment significantly ($p < 0.05$) affected photosynthetic total conductance value compared to control plots at the serious drought conditions in the 2022 season for both growing stages BBCH51 and BBCH77, showing the highest physiological response of the spring oats to the application of foliar nutrients through the leaves. During the serious drought (2022) conditions at the BBCH51 growing stage, the highest value was measured with Si+S foliar application ($0.125 \text{ mol m}^{-2} \text{ s}^{-1}$), and for the BBCH77 growing stage, the highest value was measured with S foliar treatment ($0.053 \text{ mol m}^{-2} \text{ s}^{-1}$). Furthermore, during the serious drought conditions growing seasons, the lowest total conductance rate for each stage (BBCH51 and BBCH77), was found in control $0.05 \text{ mol m}^{-2} \text{ s}^{-1}$ and $0.025 \text{ mol m}^{-2} \text{ s}^{-1}$, respectively.

For the mild drought seasons (2023) the sole foliar application of Si and S showed the highest photosynthetic total conductance during the BBCH51 and BBCH77 growing phase with a value of $0.248 \text{ mol m}^{-2} \text{ s}^{-1}$ and $0.305 \text{ mol m}^{-2} \text{ s}^{-1}$, respectively. However, the lowest photosynthetic total conductance during the mild drought conditions (2023) was found with the Si+S foliar treatment $0.114 \text{ mol m}^{-2} \text{ s}^{-1}$ at BBCH51, and the control treatment, with a mean of $0.241 \text{ mol m}^{-2} \text{ s}^{-1}$ at BBCH77 growing phase. (Figure 20)

Statistically significant results observed in the photosynthetic total conductance analysis under foliar treatments and seasonal conditions mark that the regulation of the total conductance parameter is a dynamic process influenced by water availability and foliar treatment strategies through the specific growing stage. The increased value of total conductance under serious drought conditions after foliar treatments gives a significant role of the Sulfur and Silicon application in improving the physiological total conductance efficiency.



Figure 20: Photosynthetic Total Conductance response in spring oat under C, S, Si, Si+S foliar treatments, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought (2022) and mild drought (2023) seasons. (Debrecen, 2022, 2023)

Note: Clustered columns show annual mean values averages across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

4.2.3.2 Photosynthetic Total Conductance Dynamics among Genotypes at Different Growth Stages

The varietal differences were statistically significant ($p < 0.05$) in the photosynthetic total conductance parameters at the BBCH39 and BBCH73 growing stage of the studied spring oats varieties under a moderate drought year (2024). The figure shows the response of the total conductance rate to selected varieties during the BBCH39 and BBCH73 growing stages of spring oats throughout the moderate drought environmental conditions.

The highest total conductance rate at the flag leaf stage during the moderate drought seasons was reached by varieties Lota and Mv Szellő with a mean of 0.2644 and 0.2537 $\text{m}^{-2} \text{s}^{-1}$, respectively. In addition, Mv Pehely showed the highest total conductance value at the early milk phenological phase with a mean of 0.2889 $\text{m}^{-2} \text{s}^{-1}$. However, Mv Pehely at the flag leaf stage showed the lowest total conductance rate, 0.1975 $\text{m}^{-2} \text{s}^{-1}$. Furthermore, Mv Méné's genotype reached significantly ($p < 0.05$) the lowest total conductance value at flag leaf stage with an average of 0.2465 $\text{m}^{-2} \text{s}^{-1}$. (Figure 21)

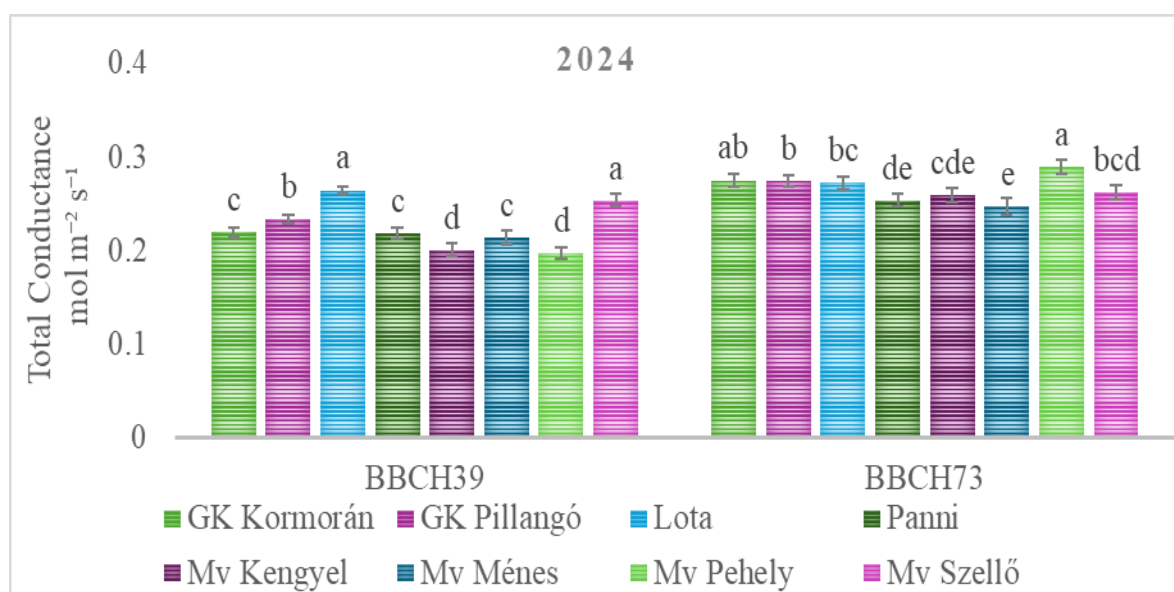


Figure 21: Photosynthetic Total Conductance response in spring oat varieties, during flag leaf (BBCH39) and early milk stage (BBCH73) in moderate drought season (Debrecen, 2024).

Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same phenological growing stage, determined by LSD at $p \leq 0.05$ significance level.

The results in the Figure 22 showed that varietal differences were statistically significant ($p < 0.05$) in the photosynthetic total conductance parameters at the BBCH51 and BBCH77 growing stage of studied spring oats varieties under serious and mild drought environmental seasons. The figure shows the response of the total conductance rate to selected eight varieties during the BBCH51 and BBCH77 growing stages of spring oats throughout the two consecutive growing seasons.

There were so many significant differences ($p < 0.05$) that affected the total conductance rate detected under the same growing phase or different growing seasons across the analyzed varieties. The highest total conductance rate was detected at variety Panna during mild drought seasons (2023) at the BBCH77 growing phase with an annual mean of $0.298 \text{ mol m}^{-2} \text{ s}^{-1}$. Furthermore, Panna showed significantly greater total conductance in the same seasons for the BBCH51 phase compared to other varieties, with a mean of $0.246 \text{ mol m}^{-2} \text{ s}^{-1}$. However, Mv Szellő and GK Pillangó resulted in the lowest total conductance during the mild drought seasons with a mean of $0.135 \text{ mol m}^{-2} \text{ s}^{-1}$ at BBCH51 and $0.238 \text{ mol m}^{-2} \text{ s}^{-1}$ at BBCH77 growing phase, respectively. Furthermore, Mv Szellő showed the lowest total conductance rate even during the serious drought year (2022) with a mean of $0.076 \text{ mol m}^{-2} \text{ s}^{-1}$ at BBCH51 growing phase and in the BBCH77 stage with GK Kormorán, Panna, and Mv Pehely showed an annual mean for each of varieties $0.03 \text{ mol m}^{-2} \text{ s}^{-1}$. Variety Lota showed a great total conductance value during the BBCH51 growing phase for serious drought (2022) with a mean of $0.107 \text{ mol m}^{-2} \text{ s}^{-1}$. In addition to the same growing season, Mv Ménes showed the highest total conductance rate at BBCH77 with a mean of $0.0570 \text{ mol m}^{-2} \text{ s}^{-1}$.

The results in total conductance rate at BBCH51 and BBCH77 stages of spring oats indicate that the response of the total conductance is strongly interacted with BBCH developmental stages, genetic variation, and drought conditions. The highest conductance values were observed during the mild drought seasons (2023), reflecting a spring oat capacity to maintain stomatal opening to enable photosynthetic activity during the analyzed stages. In contrast, the significant decrease of total conductance in the BBCH77 stages resulted in stomata closure. The explained variability between spring oat genotypes suggests that some of them exhibit a higher total conductance rate in the early growth stage, while others maintain a higher rate during the late milking phase.

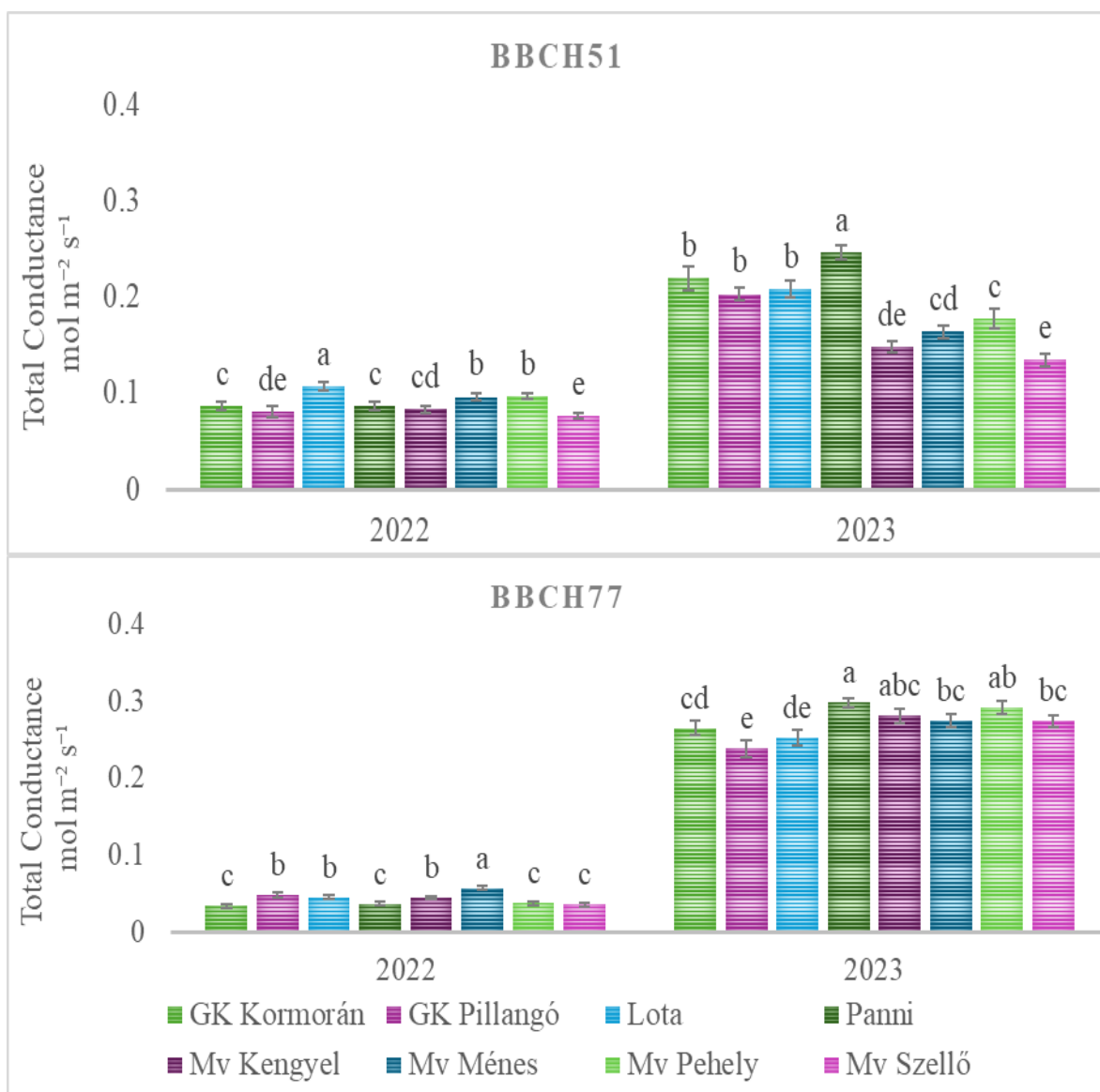


Figure 22: Photosynthetic Total Conductance response in spring oat varieties, during beginning of heading (BBCH51) and late milk stage (BBCH77) under serious drought (2022) and mild drought (2023) seasons. (Debrecen, 2022, 2023)

Note: Clustered columns show annual mean values averages across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same growing season, determined by LSD at $p \leq 0.05$ significance level.

4.3 Effect Silicon and Sulfur Foliar Treatments on the Thousand Grain Weight and Grain Yield of Spring Oat Genotypes

4.3.1 Effect of Silicon and Sulfur Foliar Treatments on the Thousand Grain Weight of Spring Oat Genotypes

Thousand grain weight (TGW) resulted in significant differences between seasons, while within the same seasons, there were no statistical differences ($p > 0.05$) between foliar applications. In the three analyzed seasons (2022-2024), all the foliar treatments are identified with the same letter, showing that those applications in the grain mass did not affect it. However, annual variations were observed between serious mild and moderate drought conditions, where the highest TGW were recorded at the 2023 season, followed by 2024, and in 2022, it is characterized by the lowest values. Furthermore, the lowest values found in serious drought conditions indicate that climatic conditions during the grain filling period were an important factor in the grain weight. The effect of foliar treatment with no significant differences indicates that the thousand grain weight is controlled by the environmental conditions mainly during grain filling phenological phase. (Figure 23)

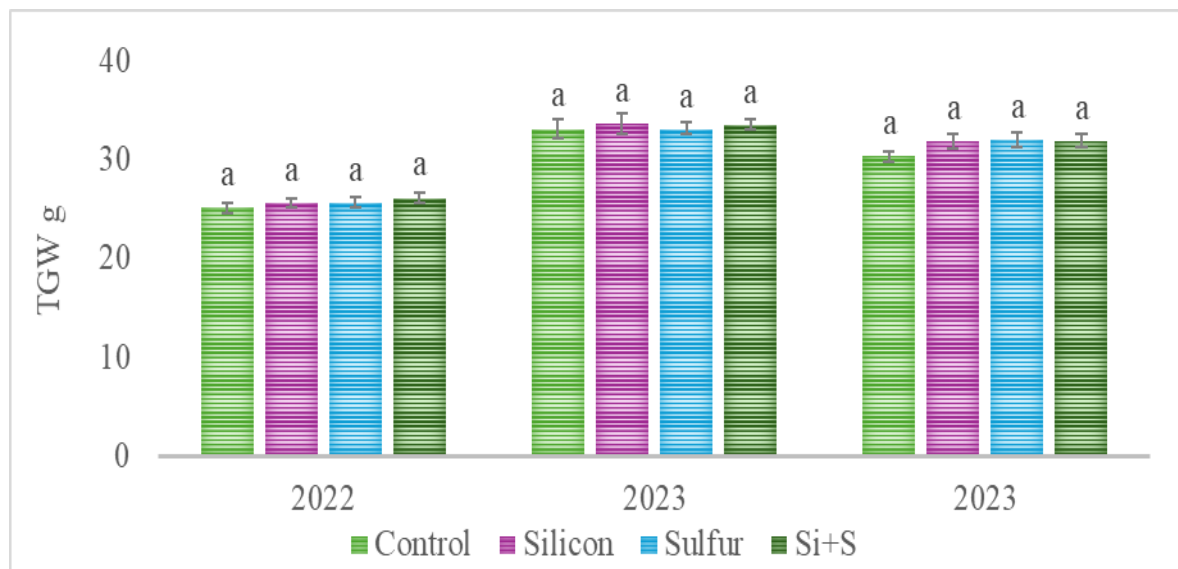


Figure 23: Thousand Grain Weight response in spring oat under C, S, Si, Si+S foliar treatments (Debrecen, 2022-2024).

Note: Clustered columns show average values across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

Figure 24 shows the effect of the varieties on the thousands grain weight (TGW) over the three growing seasons (2022 – 2024), where significant differences were observed during the cultivation years and between the varieties within the same season. The serious drought conditions (2022) present the lowest TGW values overall seasons, and the genotypes were statistically significant ($p < 0.05$). Lota genotype showed the highest TGW with a mean of 28.89 g, while the GK Kormorán reached the minimum value with a mean of 23.06 g.

The year 2023, is characterized by mild drought conditions the TGW was increased significantly compared to all cultivation years. However, the varieties are grouped with the same letter, showing a none significant difference between them, coming with a strong suggestion that the climatic conditions are an important factor for the grain filling process. In the 2024 season, TGW values are higher than in 2022 and relatively lower than in 2023.

From the figure 23, we can identify that TGW values are more influenced by the season factor than the genotype differences in the optimal environmental conditions, while in a stress drought year, the genetic differences are highly pronounced by determining the genotype x environment interaction for the grain weight results.

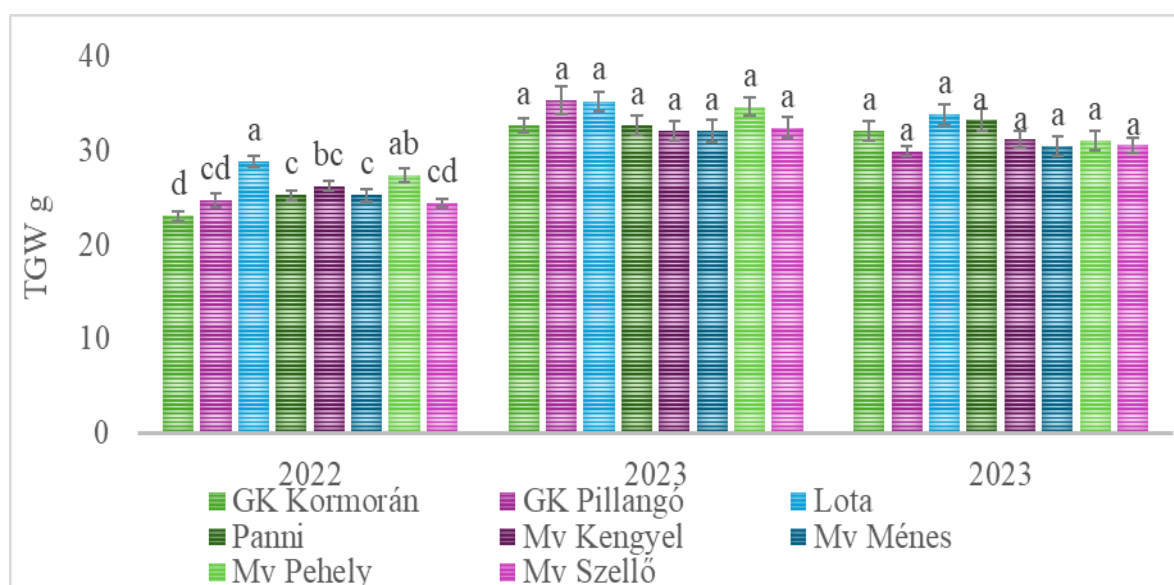


Figure 24: Thousand Grain Weight response of spring oat varieties, during three cultivation years (Debrecen, 2022 – 2024).

Note: Clustered columns show average values across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

4.3.2 Effect of Silicon and Sulfur Foliar Treatments on the Grain Yield of Spring Oat Genotypes

The presented results in Figure 25 shows that spring oat grain yield response to silicon, sulfur, and a combination of them, is statistically significant ($p < 0.05$) under the same growing season, and strongly dependent on environmental factors during the cultivation period. The overall decrease in grain yield was observed during the serious drought season (2022) as a result of water availability. The foliar treatment with sulfur and a combined silicon and sulfur application gives a relative advantage under serious drought conditions, suggesting a higher yield performance with a mean of 3592 kg ha^{-1} and 3224 kg ha^{-1} , respectively. However, a sole application of Silicon resulted in the lowest yield performance during the serious drought year with a mean of 2767 kg ha^{-1} . Statistical classification ($p < 0.05$) of foliar application confirms a dominant role of the sulfur from other treatments under serious drought conditions by direct maintenance of metabolic processes and grain filling. The weaker effect of sole silicon application compared to control under the serious drought conditions showed the insufficient availability to affect yield performance.

The 2023 season was characterized by mild drought conditions. The performance of the grain yield reached the highest record during this season in all treatments compared to other study years, showing that the favorable environmental conditions have expressed the full productivity potential by improving the grain production of spring oats. The sulfur foliar application resulted in the highest grain yield production with a mean of 6533 kg ha^{-1} , followed by a combined application of silicon and sulfur 6427 kg ha^{-1} , while the silicon and control foliar application showed the lowest values, 5924 and 6322 kg ha^{-1} , respectively. The results from the mild drought year emphasize that sulfur applications support the nutrition uptake into increasing the grain yield performance. The positive performance of silicon and sulfur treatment showed a positive interaction of silicon and sulfur on nutrition uptake and grain filling, although the applied combination resulted in lower yield production compared to sole sulfur application. In contrast, the lower yield productivity was observed in the silicon sole application during the mild drought seasons and was a negative factor on grain yield performance.

The 2024 production season is characterized by moderate drought conditions, showing an intermediate season between extreme drought stress (2022) and mild drought conditions (2023), giving a better overview of yield stability based on the intensity of drought stress. Grain yields in this production season were significantly ($p < 0.05$) compared to 2022 and to the 2023 production season, reflecting the importance of environmental conditions on yield stability. Sole sulfur application and a combination of it with silicon resulted in higher grain yields (5628 kg ha^{-1} and 5499 kg ha^{-1}), which showed a statistically significant difference ($p < 0.05$) with control and sole silicon foliar treatment, confirming that under moderate stress conditions (2024) the foliar treatment with applying nutrient elements is an important factor for grain yield productivity.

Significant difference ($p < 0.05$) from 2022, where sulfur showed a higher grain yield performance, during the 2024, the differences between sole sulfur application and combination with silicon were only 2.29% higher, suggesting that under moderate stress conditions (2024), silicon may play a supporting role but not a dominant factor for grain yield improvement. Sole silicon foliar treatment resulted in lower yield productivity compared to treatments that include sulfur, which suggests that during our experiment in spring oat grains, silicon is not sufficient to promote the grain filling process in the current environmental conditions.

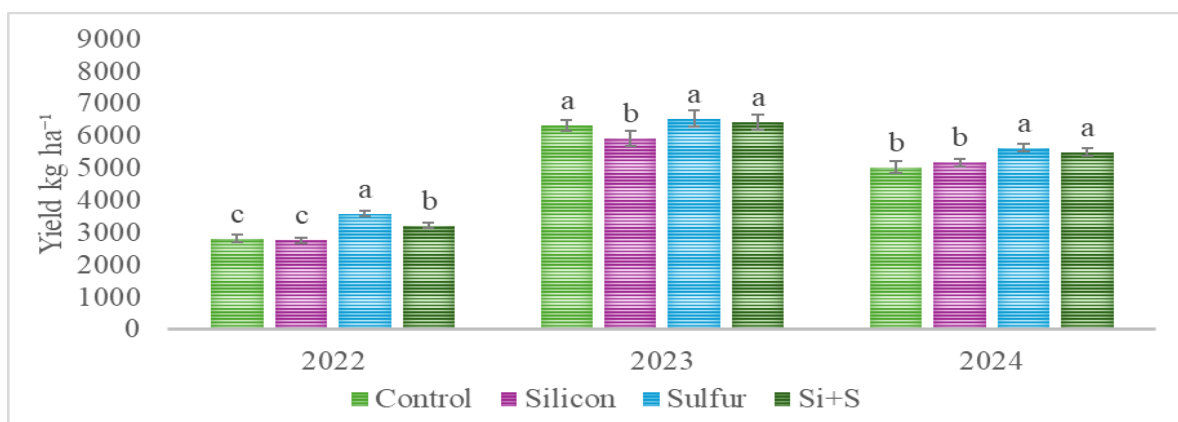


Figure 25: Grain Yield response in spring oat under C, S, Si, Si+S foliar treatments (Debrecen, 2022-2024).

Note: Clustered columns show average values across 8 varieties and 3 replications, with ± 24 standard error of means. Same letter in different treatments means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

Grain yield experimental data for eight spring oat genotypes over the three production seasons (2022-2024) showed the statistically significant ($p < 0.05$) factor of environmental conditions and varietal divergences in response to grain yield productivity. In the serious drought conditions year (2022), yields were significantly ($p < 0.05$) lower in all varieties compared to other production years and within the same period, reflecting a lower grain filling capacity during the serious drought conditions. However, during these serious environmental drought conditions, there were significant differences ($p < 0.05$) between the studied genotypes, with a mean ranging from 2295 kg ha⁻¹ in GK Kormorán to 3549 kg ha⁻¹ in the Panna genotype. The varieties Lota (3309 kg ha⁻¹), Mv Kengyel (3343 kg ha⁻¹) and Mv Szellő (3331 kg ha⁻¹) resulted relatively higher grain yield compared to Mv Pehely (3163 kg ha⁻¹), Mv Ménes (2955 kg ha⁻¹) and GK Kormorán (2295 kg ha⁻¹), suggesting a slightly better drought stress tolerance and capacity for grain filling physiological processes under serious drought production parameters.

In the mild drought season (2023), the highest yield was recorded in all varieties compared to the serious drought (2022) and moderate drought (2024) seasons, expressing spring oat genetic potential under mild drought conditions. Grain yield ranges from 4330 kg ha⁻¹ (GK Kormorán) to 8003 kg ha⁻¹ (Mv Ménes), resulting in a significant varietal differentiation. Varieties Panna (7050 kg ha⁻¹), Mv Szellő (6419 kg ha⁻¹), Mv Pehely (6333 kg ha⁻¹), Mv Kengyel (6334 kg ha⁻¹), Lota (6061 kg ha⁻¹) and GK Pillangó (5879 kg ha⁻¹) resulted in higher yields compared to other production seasons indicating a great efficiency in photosynthetic utilization and reproductive capacity potential under favorable climatic conditions. GK Kormorán showed the lower grain yield production (4330 kg ha⁻¹) during the mild drought production year.

Production season in 2024 is characterized by moderate drought conditions, the highest yield is recorded in all varieties compared to the serious drought environmental production year (2022), which indicates a great genetic potential expression. Grain yields range from the lowest variety GK Kormorán (4240 kg ha⁻¹) to the highest production variety Mv Ménes (6031 kg ha⁻¹). Varieties Panna (5071 kg ha⁻¹), Mv Szellő (5500 kg ha⁻¹), Mv Pehely (5727 kg ha⁻¹), Mv Kengyel (5074 kg ha⁻¹), Lota (5132 kg ha⁻¹) and GK Pillangó (5279 kg ha⁻¹) resulted in higher yields compared to serious drought production seasons (2022) indicating a

moderate efficiency in photosynthetic utilization and reproductive capacity potential under favorable climatic conditions. Compared to a mild drought year, the decline in grain yield during the moderate drought year were presented significantly ($p < 0.05$) in all varieties. Furthermore, during the moderate production, the efficiency of physiological stress management such as water use efficiency, is strongly suggested for stress management, serving as a key indicator of production stability, varietal differentiation for maximum yield achievement under moderately stressful environmental conditions. (Figure 26)

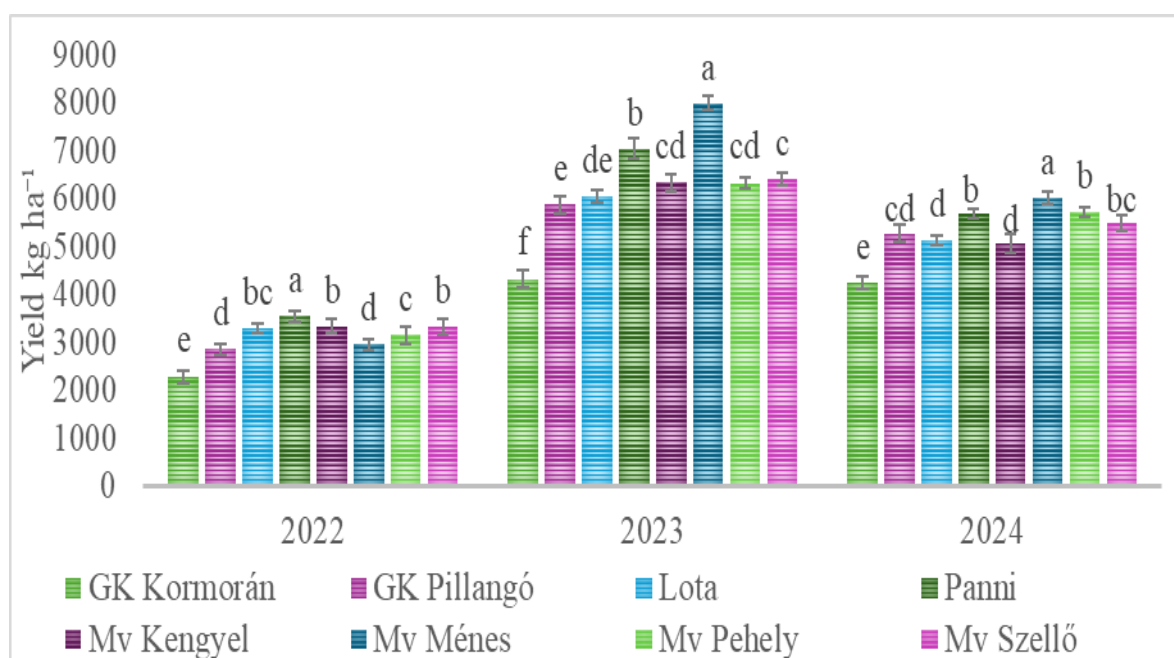


Figure 26: Grain Yield response of spring oat varieties, during three cultivation years (Debrecen, 2022-2024).

Note: Clustered columns show average values across 4 treatments and 3 replications, with ± 12 standard error of means. Same letter in different variety means no significant difference within same growing seasons, determined by LSD at $p \leq 0.05$ significance level.

It was observed that sulfur application performed significantly better compared to sole silicon and a combined silicon and sulfur application. Furthermore under serious drought conditions the sole sulfur foliar application increased the yield by 22.9% compared to control. While during the mild drought conditions yield were improved by 3% of sole sulfur application. During the moderate drought conditions the yield improvement were 10.5% compared to control with sole sulfur foliar fertilization.

4.4 Effect Silicon and Sulfur Foliar Treatments on the Grain Macro- and Microelement Content of Spring Oat Genotypes

4.4.1 Effect of Silicon and Sulfur Foliar Treatments on the Macroelement Content of Spring Oat Genotypes

4.4.1.1 Macroelement Content of Grains in Response to Foliar Application of Silicon and Sulfur

Leszczyńska et al. (2023) reported the essential macro and micro elements found in oats and their nutritional importance for human benefits. From the experimental findings, it is important to mention the positive effect of foliar application of silicon and sulfur, and the climatic parameters influenced the grain mineral content of the spring oats. The serious drought season (2022) showed a positive effect of a combined foliar application of silicon and sulfur. However, under mild drought conditions (2023) the sole foliar application of sulfur were highly effective. Furthermore, under the moderate drought conditions of the 2024 season, the sole application was performing the best compared to other foliar treatments. From these findings, the foliar treatments of silicon and sulfur are highly influenced by the intensity of the drought on the spring oat grain quality performance. Specifically, optimization of the foliar application highly supports the sustainable spring oat grain quality.

The analyzed macroelements in the Hungarian spring oat grain were potassium – K, phosphorus – P, calcium – Ca, sulfur – S and magnesium - Mg. The highest macroelement accumulation in the grain of spring oats was K and P compared to Ca, S, and Mg. The analyzed macroelements significantly showed differences ($p < 0.05$) across the cultivation seasons and the foliar application, highlighting the influence of year and foliar application on the grain nutrient content. A sole or combined application of silicon and sulfur was highly influenced by the availability of water during the cultivation seasons. During the mild or moderate growing seasons, the sole application of sulfur resulted in the increase of the macroelement content in the spring oat grains. However, under serious environmental stresses during the 2022 cultivation season, a combined silicon and sulfur application showed the best performance for the macroelement concentration.

Potassium content in the spring grain during the serious drought year of 2022 ranged between (6777-7304 mg kg⁻¹), while approaching nearly double (2023: 3548-4230 mg kg⁻¹, 2024:

2673-3289 mg kg⁻¹) those observed in seasons with more favorable water availability. Nevertheless, a significantly lower grain K concentration was detected only under the silicon (6777 mg kg⁻¹) treatment, whereas the control (7243 mg kg⁻¹), sulfur (7289 mg kg⁻¹), and combined Si+S (7304 mg kg⁻¹) treatments exerted statistically indistinguishable effects on potassium accumulation. In both 2023 and 2024, all applied treatments resulted in significantly higher potassium concentrations compared with the control (2023: 3528 mg kg⁻¹, 2024: 2673 mg kg⁻¹) plots, and the influence of each treatment was statistically verified. The highest K concentrations were observed under S application (2023: 4230 mg kg⁻¹, 2024: 3239 mg kg⁻¹), followed by the combined Si+S treatment (2023: 3995 mg kg⁻¹, 2024: 3010 mg kg⁻¹), and subsequently the Si foliar treatment (2023: 3872 mg kg⁻¹, 2024: 2896 mg kg⁻¹) (Figure 27). It was observed that during the cultivation seasons, the total precipitation showed a negative correlation ($r = -0.663$) and a positive correlation with PaDi index ($r = 0.696$) with the Potassium content. (Table 9) The sulfur foliar treatment overall showed the best performance on the K content in spring oat grain.

The relationship between water availability during the growing season and the phosphorus content of oat grain appears to be less straightforward. In the control plots and those treated with silicon, higher grain phosphorus concentrations (C: 5178, Si: 5459 mg kg⁻¹) were observed in the favorable, good water supplied 2023 season. However, in the sulfur treated (2022: 5449, 2023: 5709 mg kg⁻¹) and combined Si+S foliar-treated (2022: 5676, 2023: 5561 mg kg⁻¹) plots, nearly identical, higher P concentrations were measured in both the well-watered 2023 season and the extremely dry 2022 season. The effect of each treatment differed significantly across all years, with the lowest phosphorus values consistently recorded in the control treatment. In 2022, the highest P content was obtained under the combined Si+S treatment (5676 mg kg⁻¹), whereas in 2023 and 2024 the sulfur treatment resulted in the greatest phosphorus accumulation. The positive effect of sulfur foliar application on phosphorus content is indicated by the fact that treatments containing sulfur resulted in significantly higher phosphorus levels in every growing season.

The treatments containing sulfur had a positive effect on the sulfur concentration in the grain. S concentrations were significantly higher under the Si+S foliar application in the 2022 season (2291 mg kg⁻¹), whereas the sole S foliar application resulted in increased S

accumulation for the 2023 and 2024 seasons, with grand means of 1923 mg kg⁻¹ and 1900 mg kg⁻¹, respectively. These findings indicate seasonal variability in S concentration in response to the different foliar treatments and demonstrate the significant influence of both S and Si+S applications on S content in spring oat grain (Figure 27). However, a negative correlation where $r = -0.475$ resulted for cultivation seasons and water content on the grain sulfur concentration. (Table 9)

The magnesium concentration in spring oat grain exhibited substantial variability as influenced by foliar treatments and genotypic differences. The Si+S foliar application proved particularly effective in 2022, enhancing grain Mg content by 16% relative to the control. In addition, sole S foliar treatment increased Mg concentration in 2023 and 2024 by 9.5% and 8.1%, respectively. Across all seasons, the control plots consistently showed the lowest Mg levels, underscoring the pronounced effect of foliar sulfur and silicon supply on enhancing magnesium accumulation in spring oat grain (Figure 27). Magnesium concentration was significantly positively impacted by the foliar application where r resulting in 0.578. (Table 9)

Similar to the other examined macronutrients, in Figure 27 it is shown the calcium concentration was positively influenced by both the sulfur and the silicon + sulfur foliar treatments. Sole application of S resulted in the highest Ca content in 2023 and 2024, with grand means of 1246 and 1253 mg kg⁻¹, respectively, corresponding to 23.5-24.1% increase compared with the control treatment. These findings highlight the effectiveness of sulfur-based foliar treatments in enhancing Ca accumulation in spring oat grain. Calcium concentration was significantly positively impacted by the foliar application where r resulted in 0.497. (Table 9)

Overall, based on the foliar application data in spring oat grain across different varieties and climatic conditions, Si alone did not result in significant increases in macroelement content. The combined Si+S foliar treatment led to the highest accumulation of K, P, S, Mg, and Ca during the extremely dry 2022 season, whereas sole application of S resulted in greater accumulation of these macroelements in 2023 and 2024. Further research is warranted to elucidate the interactions among foliar nutritional treatments and climatic factors to enhance and improve the grain nutritional quality of oats.

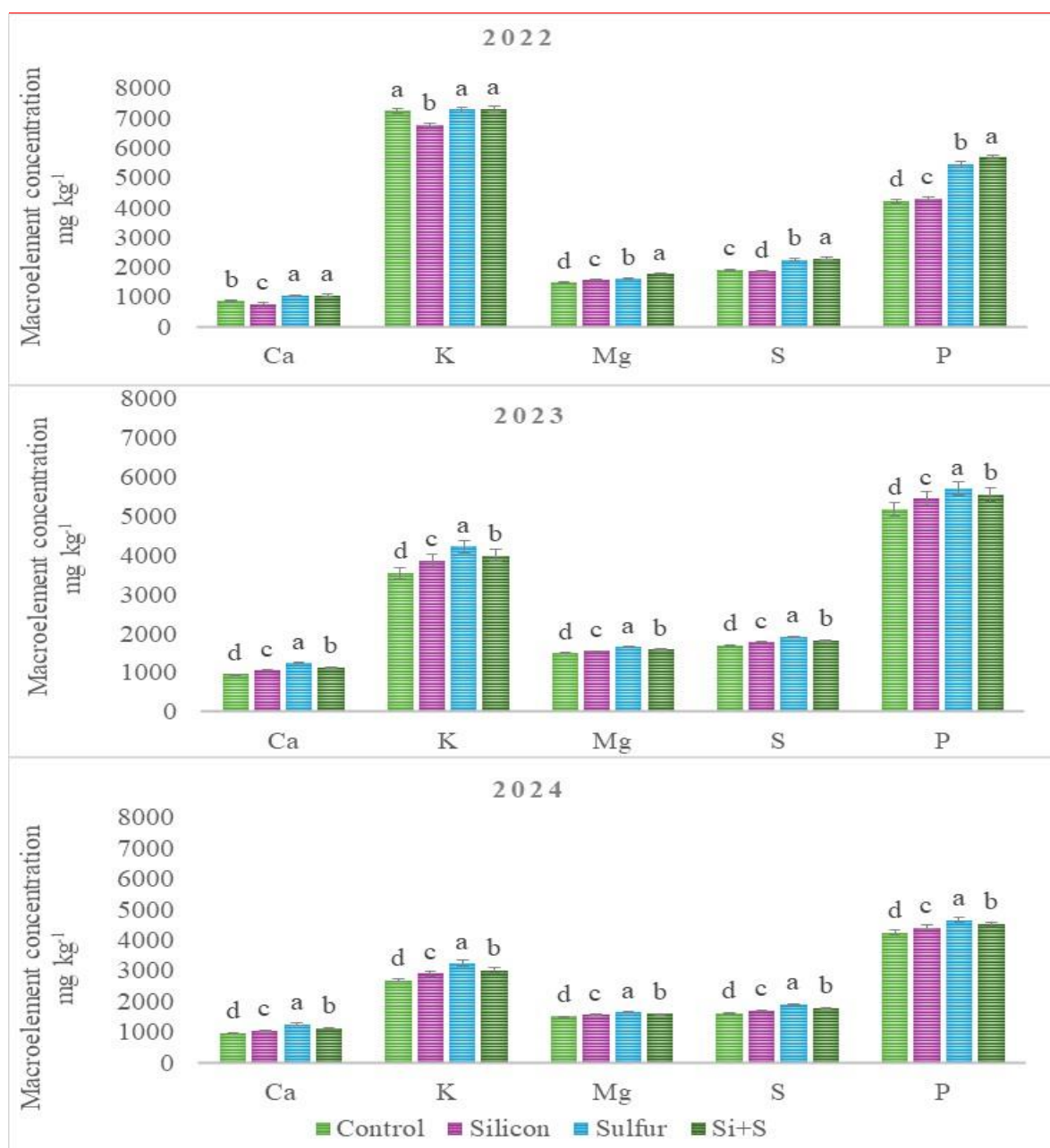


Figure 27: The macroelement concentration in spring oats whole grains under sole and combined silicon and sulfur application (Debrecen, 2022-2024).

Note: Average values are presented in columns for eight varieties and three repetitions ($n = 24$), $\pm$ standard error. Concentration in the same macroelement and same cultivation seasons presented with different letters shows significant differences for foliar application (LSD statistics at $p \leq 0.05$).

In the present spring oat experiment, the sulfur treatment increased significantly the potassium content during serious drought condition (2022), recommending the internal elemental uptake. From our experiment the calcium and magnesium concentration were significantly higher by foliar application of sulfur. Similar findings were achieved in the spring wheat, where foliar sulfur treatment increased the magnesium and calcium content (Brodowska and Kaczor., 2012)

Silicon element has a crucial role on the macroelement uptake. Scientific researchers have reported the role of silicon in the magnesium and phosphorus accumulation in tissues of the crops (Greger, 2018; Schaller., 2021). Specifically, under serious drought environmental conditions, silicon increases the water content status in crops. From the scientific literature it has been showed that under the climatic conditions with optimal temperature and controlled irrigation, there were no significant phosphorus, magnesium, and calcium accumulation on the wheat grains (Schaller., 2021). However, from our experiment it has been found that during the mild dry season in 2024, the calcium, phosphorus, and magnesium concentrations have increased significantly by foliar treatment with silicon. The scientific studies with silicon foliar treatments on the cereals, specifically on the wheat varieties under drought conditions, reported a decrease of potassium concentration and increase of phosphorus. Our result proved the same significant increase in phosphorus (Helal et al., 2022). Furthermore, the amount of calcium resulted in higher concentration in our experiment in spring oats, while scientific findings reported the higher content of calcium compared to triticale, barley, and millet (Torbica et al., 2021). Under the serious drought conditions, the silicon foliar treatment had a significant effect on the accumulation of potassium, sulfur, and magnesium in the sunflower genotypes (Gunes et al., 2008). From our results shown similarities in the magnesium accumulation. In contrast, the potassium, sulfur and calcium resulted negatively for the silicon foliar application parts. From our experimental analysis, a combined application of silicon and sulfur foliar application performed the best under serious drought conditions by increasing the potassium content (Li et al., 2018).

4.4.1.2. Macroelement Content of Grains of Spring Oat Genotypes

The findings presented in Figure 28 show the macroelement content significant variation ($p < 0.05$) throughout the cultivation years and the genotypes presenting a variety and cultivation seasons dependent factor on the macroelement content.

For potassium, the results showed substantial variability both across varieties and seasons. In the 2022 serious drought season, the highest K concentration was recorded in ‘Mv Pehely’ (7484 mg kg⁻¹), and ‘Mv Ménes’ (7430 mg kg⁻¹). During the mild and moderate drought seasons (2023 and 2024), ‘Mv Pehely’ (4396-3300 mg kg⁻¹) and ‘Mv Kengyel’ (4200-3660 mg kg⁻¹) achieved higher K concentrations. The lowest potassium levels were consistently observed in 2024 across all varieties, indicating a potential environmental constraint influencing nutrient accumulation. These findings suggest that both variety selection and seasonal conditions play a critical role in determining potassium concentration in oat grain, highlighting their importance in agronomic optimization strategies.

When evaluating genotypes averaged across seasons, it was similarly evident that the 2023 season was favorable for all varieties; however, the magnitude of the year-to-year variation was more pronounced in the Martonvásár-bred cultivars, while the Szeged-bred varieties GK Kormorán and GK Pillangó exhibited a smaller seasonal effect. The best performance phosphorus content was shown by the following varieties: Mv Pehely, Lota and Panna with average values (6021, 5233, and 4853 mg kg⁻¹, respectively), indicating genotype-specific responses to P availability under varying seasonal conditions.

A noteworthy outcome of the experiment was that Mv Pehely variety consistently exhibited elevated sulfur concentrations across all examined seasons (2022, 2023, 2024) with grand means of 2223, 1967, and 1958 mg kg⁻¹, respectively. This genotype demonstrated a superior capacity for sulfur accumulation in the grain compared with the other varieties, indicating a robust and stable response to varying seasonal conditions. Similarly to S accumulation, the Mv Pehely variety consistently exhibited the highest Mg concentrations in the grain throughout the three-year experimental period, demonstrating stable and significantly higher mean values across all seasons compared with the other genotypes. Additionally, the GK Kormorán variety recorded the highest mean Mg content in 2022 (1672 mg kg⁻¹), indicating

its potential as a competitive alternative under specific environmental conditions. Calcium concentrations were highest in the 'Lota' variety in 2022 ($1144.4 \text{ mg kg}^{-1}$), whereas Mv Ménes exhibited greater Ca accumulation in 2023 and 2024, with means of 1255 and 1215 mg kg^{-1} , respectively, indicating differential accumulation across seasons. These results underscore a pronounced variety x season interaction in determining Ca accumulation among different spring oat genotypes.

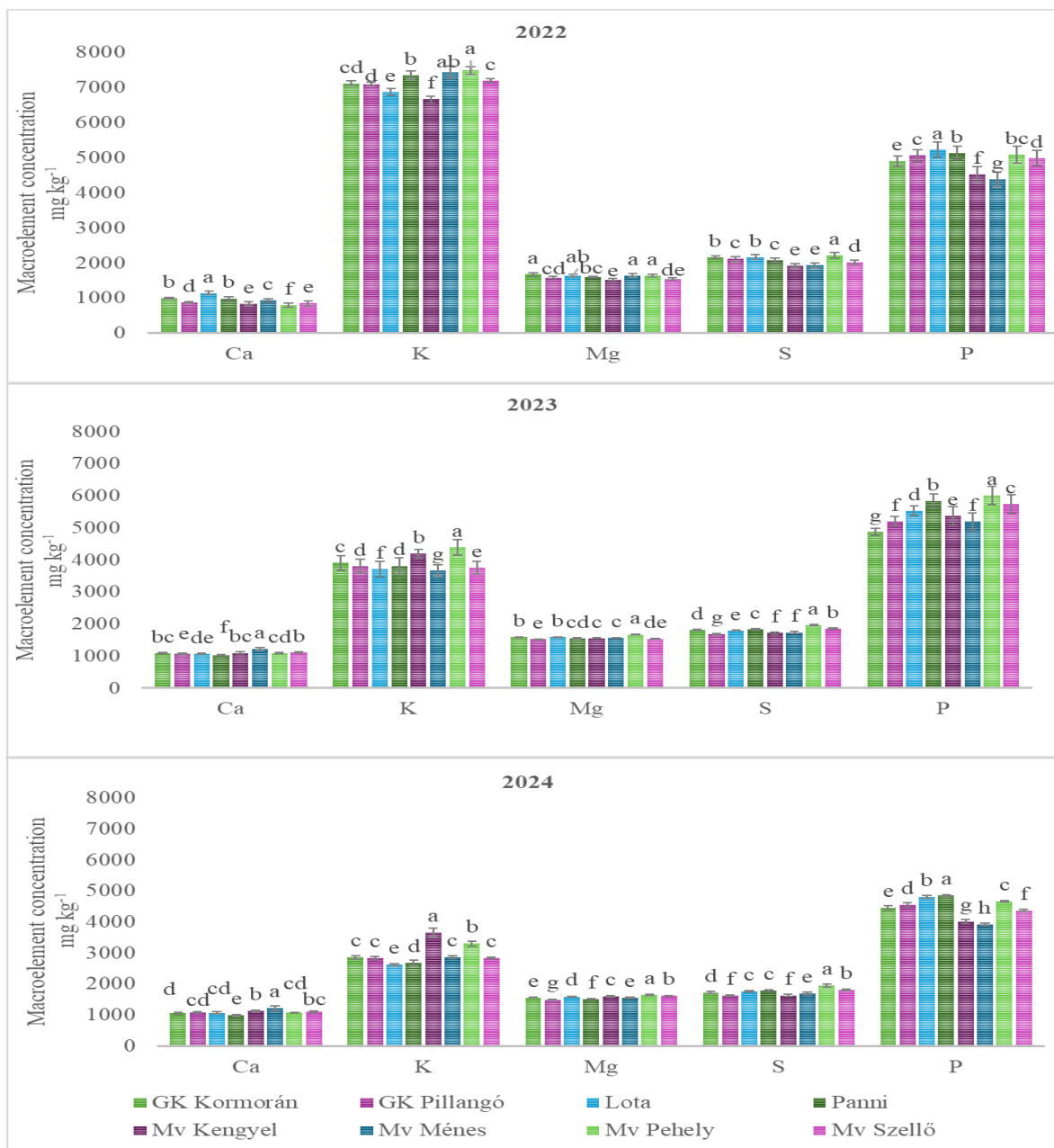


Figure 28: The macroelement concentration in grains of spring oat varieties (Debreceń, 2022-2024).

Note: The average value of four treatments and three repetitions ($n=12$), $\pm$ standard error ($n=12$) are presented in columns. Statistically difference genotypes between same macronutrient are represented with different letters indicate statistically significant differences tested with LSD at $p \leq 0.05$.

4.4.2. Effect of Silicon and Sulfur Foliar Treatments on the Microelement Content of Spring Oat Genotypes

4.4.2.1. Microelement Content of Grains in Response to Foliar Application of Silicon and Sulfur

The analysis of micronutrient concentrations in spring oat grain, as influenced by seasonal conditions and silicon and sulfur application, provides critical insights into their accumulation. Figure 29 presents the analysis and statistical evaluation of five micronutrients. These data facilitate the examination of seasonal dynamics to foliar applications, thereby enhancing our understanding of treatment x crop year interactions. Such knowledge is essential for the development of foliar management strategies targeting the optimization of oat grain nutritional quality.

The analyzed microelements in the spring oat experiment were iron – Fe, sodium – Na, manganese -Mn, copper – Cu, and silicon – Si. It is shown in the Table 9 the micronutrient in spring oat grains showed the positive foliar application in the increasement significantly on their concentration where $r = 0.368-0.596$ and $p \leq 0.01$. The results indicate that Na, Si, Fe, and Mn concentrations were significantly higher than Cu in spring oat grains. Sulfur foliar treatment resulted in the highest accumulation of Na (168 mg kg^{-1}) and Fe (62.76 kg^{-1}), whereas Si application primarily increased Si content, with a grand mean of $110.69 \text{ mg kg}^{-1}$. Furthermore, the combined Si+S treatments produced the highest mean Mn and Cu concentrations with grand means of 62.83 and 12.56 mg kg^{-1} , respectively. These findings underscore the importance of sulfur-based foliar treatments in enhancing micronutrient accumulation and optimizing foliar treatment strategies in spring oat production.

Regarding sodium, S foliar application was the most effective in the 2023 and 2024 seasons, increasing Na concentrations by 33.7 - 34.7% compared with the control. In contrast, during the serious drought season of 2022, S foliar treatment did not result in significant differences relative to the control.

Analysis of silicon concentrations in spring oat grain revealed variability across seasons. Foliar application of Si resulted in the highest Si content, reaching a maximum of $110.69 \text{ mg kg}^{-1}$, in 2024. In the 2023 season, Si treatment was also effective, with a grand mean of 98.68

mg kg⁻¹. In contrast, during the 2022 season, the combined Si+S foliar treatment produced the highest Si accumulation, reaching 81.58 mg kg⁻¹ in the grain.

Iron concentrations in spring oat grain again showed significant variations. The highest Fe content was observed under sole sulfur foliar treatment in 2023 and 2024, reaching 62.76 mg kg⁻¹, 61.61 mg kg⁻¹, respectively. Additionally, the combined Si+S application resulted in significantly higher Fe accumulation during the 2022 season, with a grand mean of 61.15 mg kg⁻¹. In contrast, sole Si application had a slightly negative effect on Fe accumulation, reducing grain Fe content by 2.2% compared with the control.

Similar to Fe, foliar application of sulfur proved most effective for manganese accumulation during the 2023 and 2024 seasons, with grand mean values of 58.21 mg kg⁻¹ and 60.24 mg kg⁻¹, respectively. In contrast, during the 2022 season, a combined Si+S resulted in the highest Mn accumulation, reaching 62.83 mg kg⁻¹, in spring oat grain.

Analogous to Na, Fe, and Mn, copper accumulation in spring oat grain was significantly enhanced by the Si+S foliar application during the 2022 season, increasing Cu content by 58% compared with the untreated control. Furthermore, sole sulfur foliar application substantially increased Cu concentrations in 2023 and 2024, by 33.5% and 60%, respectively.

Microelement concentrations in spring oat grain varied across seasons, with notable trends observed for sodium (Na), silicon (Si), iron (Fe), manganese (Mn), and copper (Cu). Analysis of the data indicates that different seasons and foliar treatments caused statistically significant differences in the accumulation of these microelements. During the 2022 season, the combined Si+S foliar treatment was the most effective in enhancing the accumulation of all studied micronutrients. Sole Si application significantly increased only Si concentrations during the 2023 and 2024 seasons. In contrast, S foliar treatment substantially enhanced Na, Fe, Mn, and Cu accumulation during the 2023 and 2024 seasons.

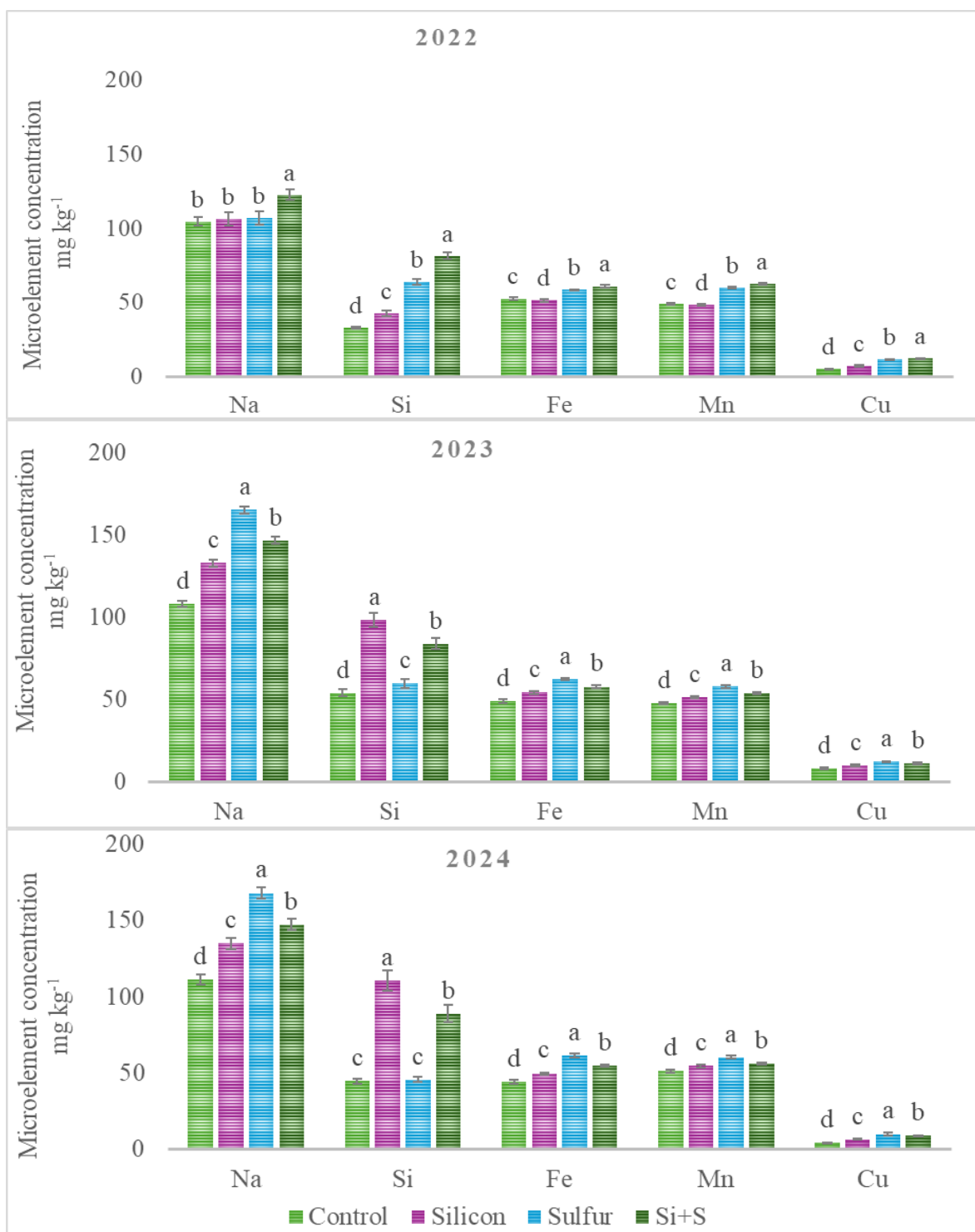


Figure 29: The microelement concentration in spring oats whole grains under sole and combined silicon and sulfur application (Debrecen, 2022-2024).

Note: Average values are presented in columns for eight varieties and three repetitions ($n = 24$), $\pm$ standard error. Concentration in the same microelement and same cultivation seasons presented with different letters shows significant differences for foliar application (LSD statistics at $p \leq 0.05$).

These results highlight the crucial role of specific foliar treatments and seasonal conditions in influencing microelement uptake. Overall, untreated control plots never reached the maximum microelement concentrations. Foliar Si application alone was effective only in maximizing Si content in 2023 and 2024, whereas the combined Si+S treatment produced significant increases across all studied microelements in 2022. Additionally, the data underscore the importance of sulfur foliar treatment in optimizing microelement content, particularly for Na, Fe, Mn, and Cu, in spring oat grain.

The foliar treatment with sulfur had a positive impact on the lupins, finding which are similar to the present experiment (Barczak et al., 2014). Furthermore, the sulfur treatment resulted in copper and manganese increase in oat grains reported from other studies (Barczak et al., 2018; Kutasy et al., 2023). Silicon has a crucial role on the microelement uptake. Scientific researchers have reported the role of silicon in the iron and manganese accumulation in tissues of the crops (Greger., 2018; Schaller., 2021). Specifically, under serious drought environmental conditions where silicon increases the water content status in crops. Under the serious drought conditions, the silicon foliar treatment had a significant effect on the accumulation of sodium, silicon, iron, manganese, and copper in the sunflower genotypes (Gunes et al., 2008). From our results we showed similarities in the silicon and copper accumulation. In contrast, the iron and manganese resulted negatively for the silicon foliar application parts, while the sodium didn't show any significant difference under the serious drought conditions. From our results, the silicon foliar application under the serious drought conditions showed a significant increase only in the silicon content, while in other microelement content, there were no significant differences, while scientific studies reported the functions in stress but not in the nutrient concentrations (Artyszak, 2018). From our experimental analysis, a combined application of silicon and sulfur foliar application performed the best under serious drought conditions by increasing the iron content (Li et al., 2018).

4.4.2.2. Microelement Content of Grains of Spring Oat Genotypes

The analysis of micronutrient concentrations in spring oat grain, as influenced by seasonal conditions and varieties, provides critical insights into their accumulation. Figure 30 presents the analysis and statistical evaluation of five micronutrients. These data show the examination of seasonal dynamics and varietal responses, thereby enhancing our understanding of genotype x season interactions. Such knowledge is essential for targeting varieties for the optimization of oat grain nutritional quality. The concentration of microelements such as sodium, iron, silicon, copper, and manganese were examined in the spring oat grain.

Sodium concentrations exhibited considerable variability both across seasons and among varieties. In 2024, ‘Mv Pehely’ showed significantly higher Na content (166.2 mg kg^{-1}) compared with the other varieties. In contrast, during 2022 and 2023, both ‘Mv Pehely’ and ‘Mv Ménes’ demonstrated higher Na accumulation, although no significant differences were observed between these two genotypes.

Silicon content exhibited considerable variability among varieties, with statistically significant differences observed. In the 2022 season, ‘Mv Pehely’ recorded the highest Si concentration (67.7 mg kg^{-1}), whereas in 2024 it showed the lowest accumulation across all genotypes. In contrast, during the 2023 and 2024 seasons, ‘Panna’ exhibited the highest Si accumulation with grand means of 96.06 and 102.2 mg kg^{-1} , respectively. The observed differences across years were statistically significant ($p < 0.05$), highlighting the importance of variety selection for enhancing Si accumulation in spring oat grain.

Among the tested varieties, ‘GK Kormorán’ exhibited the highest iron accumulation in spring oat grain across the three seasons, with grand means of 61.82 , 61.13 , and 57.71 mg kg^{-1} in 2022, 2023, and 2024, respectively. The lowest Fe concentrations were observed in ‘Mv Kengyel’ in 2022 (52.12 mg kg^{-1}), ‘Mv Ménes’ in 2023 (53.48 mg kg^{-1}), and GK Pillangó in 2024 (45.86 mg kg^{-1}).

In the 2022 season, the ‘Lota’ variety exhibited the highest manganese concentration (58.09 mg kg^{-1}), followed closely by ‘Mv Ménes’ with a grand mean of 57.58 mg kg^{-1} , with no

significant difference between them. In contrast, during the 2023 and 2024 seasons, ‘GK Kormorán’ showed the highest Mn accumulation with grand means of 61.53 and 65.29 mg kg⁻¹, respectively.

Copper concentrations exhibited a significant increase in 2023 compared with the other seasons, reaching a peak in the ‘Mv Pehely’ variety with a grand mean of 11.68 mg kg⁻¹. In 2022, the Cu concentration in ‘Mv Pehely’ was lower (10.08 mg kg⁻¹) but still significantly higher than in other varieties. GK Kormorán resulted in the highest Cu accumulation during 2024 with a grand mean of 9.135 11.68 mg kg⁻¹. In contrast, the lowest Cu concentrations were observed in ‘GK Pillangó’ (4.53 mg kg⁻¹) and ‘Mv Kengyel’ (4.445 mg kg⁻¹) during the 2024 season. These findings highlight the influence of specific seasonal conditions and varietal differences on Cu accumulation in spring oat grain.

Microelement concentrations in spring oat grain varied across seasons, with notable trends observed for sodium (Na), silicon (Si), iron (Fe), manganese (Mn), and copper (Cu). Analysis of the data indicates that different seasons and genetic variation caused statistically significant differences in the accumulation of these microelements.

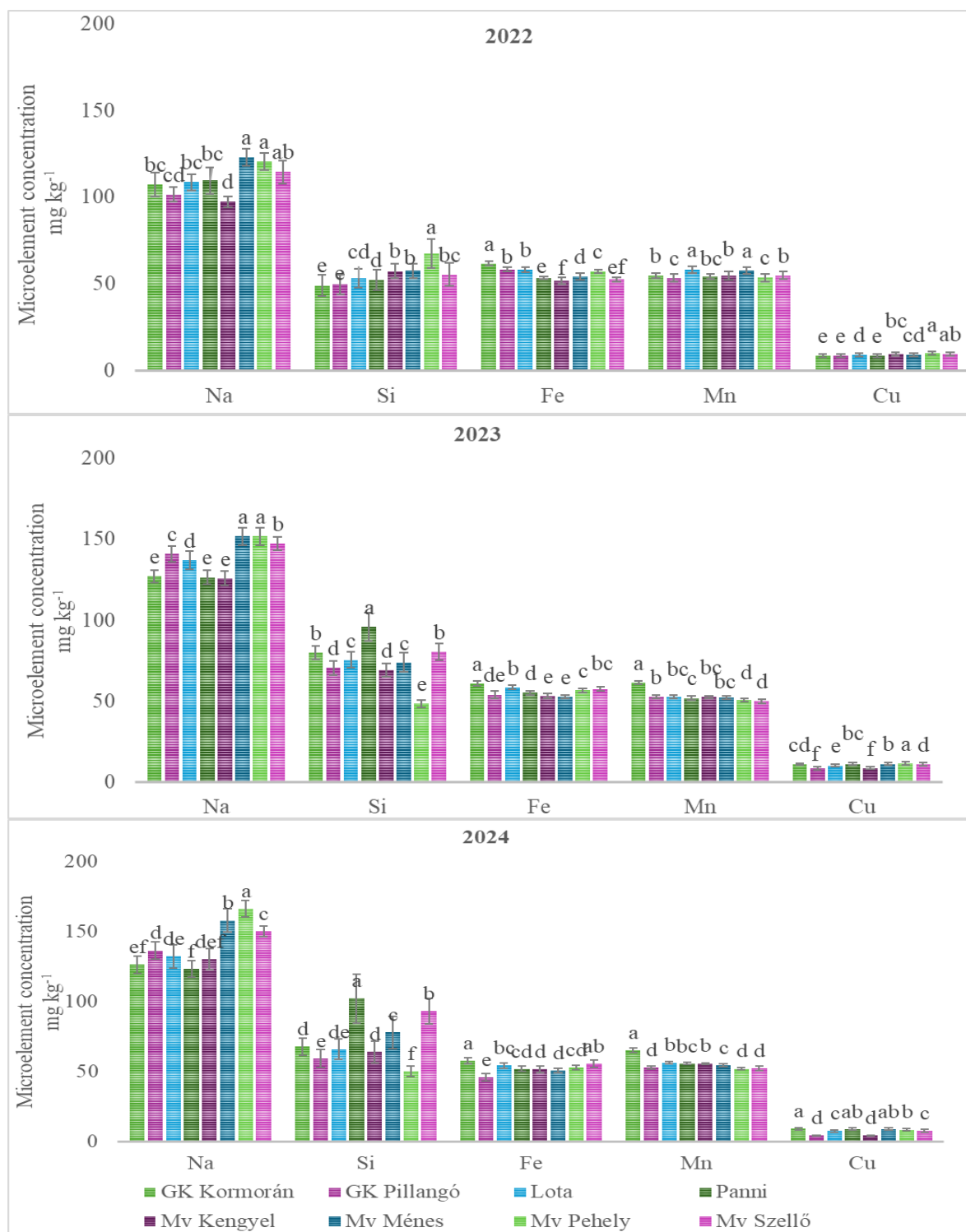


Figure 30: The microelement concentration in grains of spring oat varieties (Debrecen, 2022-2024).

Note: The average value of four treatments and three repetitions ($n=12$), $\pm$ standard error ($n=12$) are presented in columns. Statistically difference genotypes between same macronutrient are represented with different letters indicate statistically significant differences tested with LSD at $p \leq 0.05$.

Variety Panna from our findings showed similarities with the sodium content measured in the roots of sugar beets, where the silicon foliar application significantly decreased the sodium content (Artyszak, 2018). However, in other varieties, the changes in sodium content were smaller with no significant differences.

The nutritional concentration in oat and its products were determined by other researcher and have shown similarities with our spring oat mineral composition for the sodium, iron, manganese, copper and silicon content (Peterson., 1992; Halla and Palko 1987). From our results and the other scientific articles, it is common that the nutritional composition of oats significantly are affected by the climatic conditions and genetic divergences (Mut et al., 2022; Jakobsone et al., 2019; Ruja et al., 2024). In addition, for the spring oat quality optimization, the genotype and climatic conditions are important for determining the quality of its grain. Copper content in our study ranged from 4.1 to 15.9 mg kg⁻¹, similar to other scientific articles, 2.67 to 15.86 mg kg⁻¹, highly influenced by nutritional application and genotypes variation (Özcan et al., 2017).

Iron content in spring oats, its highest value reached 59.9 mg kg⁻¹, higher compared to the other scientific results, where the highest oat grain iron content reached 37 mg kg⁻¹. (Loskutov et al., 2021). In the moderate drought season, the average copper content resulted in 4.6 mg kg⁻¹, similar to the findings of Biel et al. (2020), with an average of 4 mg kg⁻¹ found. The varietal selectivity and nutritional foliar application are highly important for determining the spring oat grain quality.

4.4.3. Macro and Microelement concentrations of Grains as Affected by the Treatments, Genotypes and Environmental conditions

The content of spring oat grain in elemental composition was statistically different from the evaluated eight genotypes ($p < 0.05$). From the examined varieties the Mv Pehely recorded the highest average of potassium (5425 mg kg⁻¹), phosphorus (5710 mg kg⁻¹), sulfur (2053 mg kg⁻¹), magnesium (1662 mg kg⁻¹), and copper (11.1 mg kg⁻¹). In contrast, the mentioned variety resulted in low silicon concentration with an average of 55 mg kg⁻¹. The highest sodium and calcium content resulted in the Mv Ménes with an average value of 142 mg kg⁻¹

- 1127 mg kg⁻¹, respectively. GK Kormorán genotype resulted in higher iron and manganese content with a mean value of 61.4 mg kg⁻¹ and 59.3 mg kg⁻¹, respectively. (Table 5)

Table 5: The varietal influence on the nutritional quality of spring oats, a grand average of three seasons and four treatments (2022-2024)

Variety	Macroelements (mg kg ⁻¹)					Microelements (mg kg ⁻¹)				
	K	P	S	Mg	Ca	Na	Si	Fe	Mn	Cu
GK Kormorán	4976	4885	1930	1618	1064	121	69.7	61.4	59.3	10.4
GK Pillangó	4903	5156	1833	1546	1007	128	63.7	55.5	53.1	8.7
Lota	4773	5436	1920	1607	1097	128	68.2	58.5	54.5	10
Panna	4995	5610	1918	1566	1020	121	81.5	54.7	52.7	10.5
Mv Kengyel	5022	5098	1789	1550	1015	116	65.2	53	53.3	9.1
Mv Ménes	4931	4925	1804	1593	1127	142	68.5	53.4	54	10.7
Mv Pehely	5425	5710	2053	1662	994	141	55	57	51.8	11.1
Mv Szellő	4912	5493	1915	1544	1022	136	72.2	56	51.7	10.7
LSD_{0.05}	43	21.7	18	17.5	15.8	4.8	1.99	0.86	0.53	0.18

Note: LSD 0.05: Least Significant Difference at p=5%

The sulfur treatments achieved the best nutritional accumulation for potassium, phosphorus, sulfur, calcium, sodium, iron, manganese and copper, while a combined sulfur and silicon treatments resulted the highest magnesium and silicon concentration in terms of grand mean. Control treatments resulted in the lowest nutritional accumulation. The foliar application and genotype interaction trend were as follows for the elemental grain content: sulfur>silicon + sulfur > silicon > control. (Table 6)

Table 6: The influence of foliar application on the macro and micro elemental spring oat grain accumulation in terms of yearly and varietal average (2022-2024, Debrecen).

Treat- ment	Macroelements (mg kg ⁻¹)						Microelements (mg kg ⁻¹)			
	K	P	S	Mg	Ca	Na	Si	Fe	Mn	Cu
Control	4780	4859	1768	1493	924	107	47.3	50.5	48.4	7.3
Si	4841	5075	1802	1559	958	124	80	53.7	50.8	9.2
S	5250	5623	2032	1640	1179	146	61.5	61.5	58.9	12.3
Si+S	5098	5600	1979	1651	1113	139	83.3	59.1	57.1	11.8
LSD _{0.05}	32.4	20.4	14.8	11.6	11.4	2.7	1.26	0.7	0.47	0.13

Note: LSD0.05: Least Significant Difference at p=5%

The three different environmental conditions for cultivation years from 2022-2024 showed significant differences in the macro/micro element content of spring oats are presented in the Table 7. Serious drought conditions influenced the highest potassium, sulfur, and magnesium concentrations. However, the mild drought environmental conditions indicated the highest accumulation for phosphorus, silicon, iron, manganese, and copper accumulation in the spring oats. While moderate drought seasons influenced the sodium content accumulation in spring oats.

Table 7: A grand mean of treatments and varieties macro/micro element accumulation in spring oat grain influenced by drought climatic seasons (2022-2024, Debrecen Hungary).

Year	Macroelements (mg kg ⁻¹)						Microelements (mg kg ⁻¹)			
	K	P	S	Mg	Ca	Na	Si	Fe	Mn	Cu
2022	7153	4913	2077	1608	930	110	55.4	56.1	55.2	9.3
2023	4869	6501	1862	1580	1110	137	76.1	59.9	50.5	13.6
2024	2954	4453	1746	1569	1090	140	72.6	52.6	55.6	7.5
LSD _{0.05}	25.7	15.3	11.6	9.8	8.5	2.3	0.99	0.51	0.33	0.13

Note: LSD0.05: Least Significant Difference at p=5%

4.4.4. The Interaction between Spring Oat Genotypes, Foliar Nutrient Application and Environmental Conditions

The high partial η^2 for calcium, copper, phosphorus, and silicon shows that the varietal and treatment response were strongly influenced by the environmental cultivation seasons. The seasons climatic conditions significantly impacted the nutrient accumulation. However, iron content reported lower partial η^2 , indicating a smaller effect on the spring oat iron content across cultivation years. (Table 8)

Table 8: The interaction between spring oat genotypes foliar treatments and cultivation seasons (2022-2024, Debrecen Hungary)

Element	df	F	p	partial η^2
Si	42	33.66	0.000	0.88
P	42	29.57	0.000	0.87
Cu	42	28.70	0.000	0.86
Ca	42	26.38	0.000	0.85
K	42	17.40	0.000	0.79
S	42	8.25	0.000	0.64
Mn	42	7.29	0.000	0.61
Na	42	5.97	0.000	0.57
Mg	42	5.65	0.000	0.55
Fe	42	3.91	0.000	0.46

Note: df: degree of freedom; F: F-value; p: significance; partial η^2 : partial eta square

4.4.5. Pearson correlation analysis results of Treatments, Sum of Precipitation during the Growing Season, PaDI Values and Element Content in Spring Oat Whole Grains

The correlation in Table 9 shows several important relations for the climatic factors and grain element content in spring oats. The precipitation P₀₃₋₀₇ showed a strong negative correlation with the PaDi index, indicating that the highest precipitation reduces the drought stress during the seasons. PaDi is strongly correlated with the potassium and sulfur elements, resulting the serious drought conditions are correlated in increase of those elements. Furthermore,

calcium, copper, iron, magnesium, sodium, and sulfur are positively correlated with foliar application ($r = 0.437-0.596$, $p \leq 0.01$), indicating a positive effect of treatment application.

The water availability strongly influenced the silicon, copper, sodium, calcium, and phosphorus concentration, where a positive correlation were between precipitation ($r = 0.328$ to 0.497) and PaDi index ($r = -0.330$ to -0.465).

The analysis indicates the climatic and genetic nutrient importance on the mineral composition of spring oats.

Table 9: Pearson correlation coefficient values among treatments, sum of precipitation during the growing season, PaDI values and element content in spring oat whole grains (Debrecen, 2022-2024).

	Treatment	P ₀₃₋₀₇	PaDI	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Si
Treatment	1	0.000	0.000	0.497**	0.500**	0.542**	0.086	0.578**	0.596**	0.483**	0.288**	0.437**	0.368**
P ₀₃₋₀₇	0.000	1	-0.999**	0.442**	0.380**	0.152*	-0.663**	-0.121*	-0.257**	0.440**	0.497**	-0.475**	0.328**
PaDI	0.000	-0.999**	1	-0.447**	-0.352**	-0.132*	0.696**	0.125*	0.245**	-0.450**	-0.465**	0.494**	-0.330**
Ca	0.497**	0.442**	-0.447**	1	0.411**	0.464**	-0.281**	0.463**	0.415**	0.684**	0.363**	0.166**	0.234**
Cu	0.500**	0.380**	-0.352**	0.411**	1	0.678**	0.191**	0.396**	0.191**	0.344**	0.796**	0.437**	0.338**
Fe	0.542**	0.152*	-0.132*	0.464**	0.678**	1	0.275**	0.568**	0.451**	0.385**	0.517**	0.561**	0.178**
K	0.086	-0.663**	0.696**	-0.281**	0.191**	0.275**	1	0.268**	0.070	-0.342**	0.168**	0.687**	-0.266**
Mg	0.578**	-0.121*	0.125*	0.463**	0.396**	0.568**	0.268**	1	0.548**	0.446**	0.255**	0.629**	0.146*
Mn	0.596**	-0.257**	0.245**	0.415**	0.191**	0.451**	0.070	0.548**	1	0.241**	-0.093	0.435**	0.198**
Na	0.483**	0.440**	-0.450**	0.684**	0.344**	0.385**	-0.342**	0.446**	0.241**	1	0.214**	0.022	0.223**
P	0.288**	0.497**	-0.465**	0.363**	0.796**	0.517**	0.168**	0.255**	-0.093	0.214**	1	0.346**	0.205**
S	0.437**	-0.475**	0.494**	0.166**	0.437**	0.561**	0.687**	0.629**	0.435**	0.022	0.346**	1	-0.021
Si	0.368**	0.328**	-0.330**	0.234**	0.338**	0.178**	-0.266**	0.146*	0.198**	0.223**	0.205**	-0.021	1

*Note: P03-07: precipitation sum for period March-July; PaDI: Pálfi Drought Index value *: the correlation is significant at $p = 5\%$; **: the correlation is significant at $p = 1\%$;*

The crop is strongly related to water access and temperature conditions in the elemental composition, ion transport, and metabolic activity. The nutritional content of cereal grains in general is strongly related to the severity of the drought (Mariem et al., 2021). Our results showed the high impact of the climatic factors on the spring oat nutritional content compared to foliar application. The PaDi index with potassium and sulfur were positively correlated, while calcium, sodium, copper and phosphorus resulted in negative correlation. Our results are consistent with a scientific experimental article showing a strong temperature and precipitation influence on the grain nutritional content in cereals. Furthermore, scientific studies have reported a strong correlation between precipitation and an increase of copper and sodium content minerals stating a strong improvement in cereal nutritional content (Högy et al., 2013).

4.4.6 Principal Component Analysis Results of Silicon and Sulfur Treatments on Macro- and Microelement Content of Spring Oat Grains

The PCA - Principal Component Analysis for spring oat grain elemental concentration under serious drought conditions is shown in Figure 31, where a strong influence of foliar application with sulfur is suggested. The biplot shows clear grouping of foliar treatments, where the control and the sole silicon application are separated from the sulfur and combined silicon and sulfur foliar applications. The Dim1 and Dim2 components explain the total variance of 75.3%. Dim1 indicate the sole sulfur application had high impact on the grain nutritional composition of spring oats specifically linkage with the potassium, magnesium, calcium and iron content.

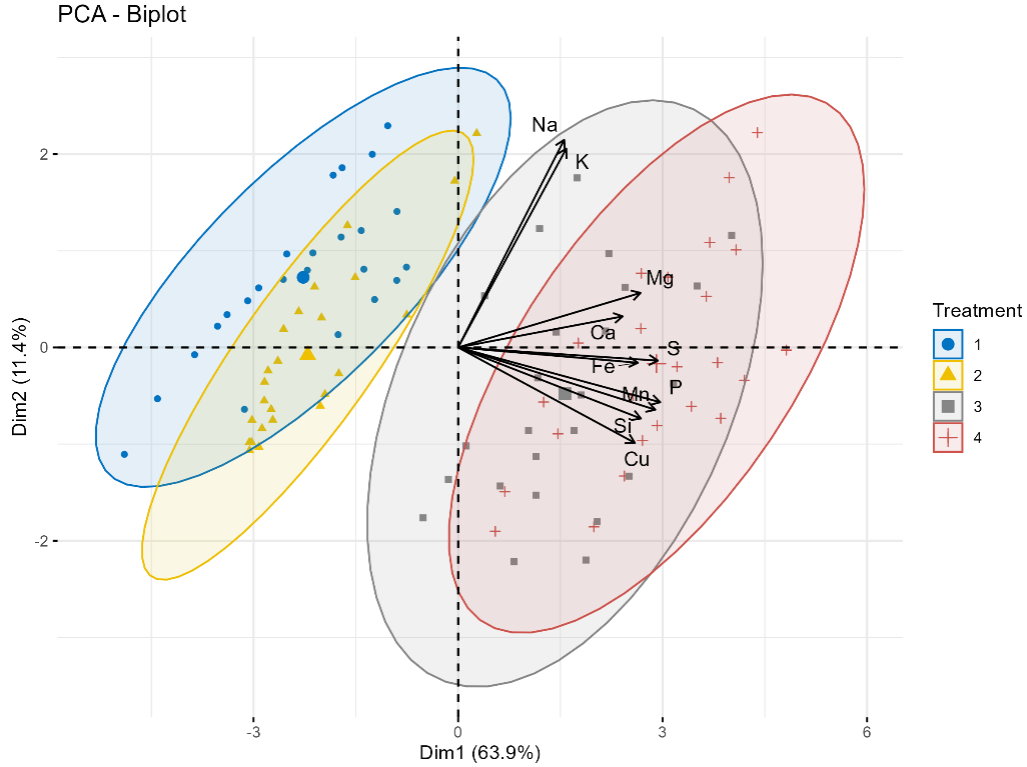


Figure 31: The illustrating of PCA - principal component analysis biplot for the relationship of treatments on macro/micro element concentration under serious drought conditions (2022). Dim1= 63.9%, Dim2 = 11.4%, making a total variability of 75.3%. Treatments. 1=control, 2=Silicon, 3=Sulfur, 4=Si+S foliar treatments.

The PCA - Principal Component Analysis for spring oat grain elemental concentration under mild drought conditions it is shown in the Figure 32, where a strong influence of foliar application with sulfur it is suggested. The biplot shows clear grouping of foliar treatments, where the sulfur and combined silicon and sulfur are separated from the control and the sole silicon application foliar applications. Dim1 explain 54.3% of the total variance indicating that the sole sulfur and combined silicon and sulfur foliar application had a high impact on the grain nutritional composition of spring oats, specifically linking with the phosphorus, sulfur, manganese, silicon, and copper element content. Furthermore, Dim2 accounts of 20.2% in total variance with highly influence of potassium and sodium distinguished parts.

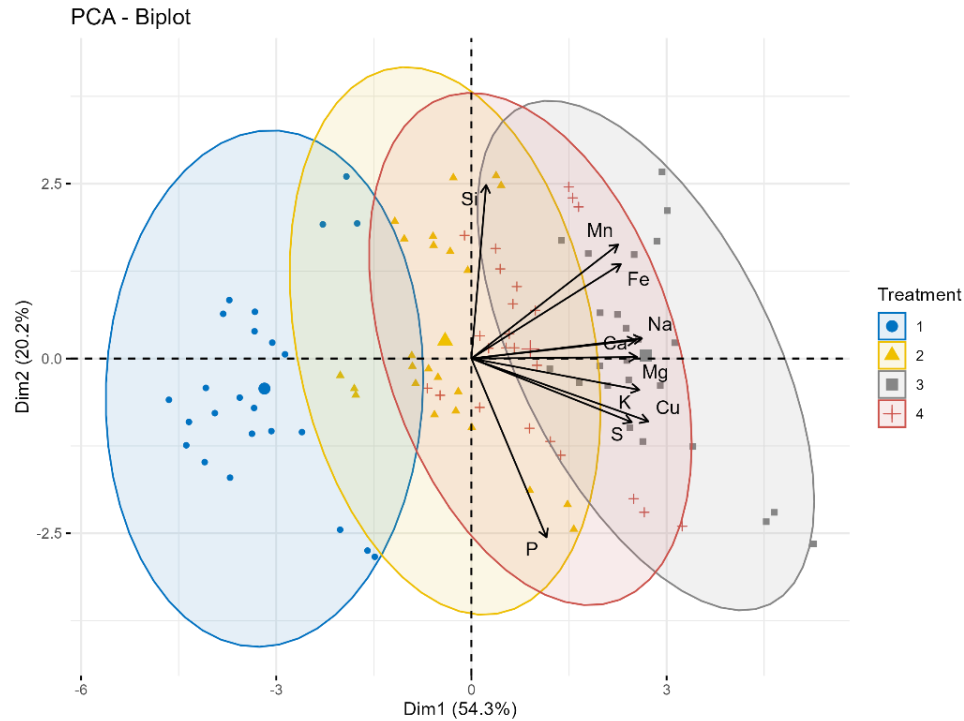


Figure 32: The illustrating of PCA - principal component analysis biplot for the relationship of treatments on macro/micro element concentration under mild drought conditions (2023). Dim1= 54.3%, Dim2 = 20.2 %, making a total variability of 74.5%. Treatments. 1=control, 2=Silicon, 3=Sulfur, 4=Si+S foliar treatments.

The PCA - Principal Component Analysis for spring oat grain elemental concentration under moderate drought conditions it is show in Figure 33, where a strong separation between foliar application and nutrient is illustrated. Dim1 explain 49 % of total variance, indicating the linkage between iron, magnesium, and sodium elements. Furthermore, Dim2 accounts of 16% in total variance with highly influence of potassium and phosphorus distinguished parts. During the mild drought conditions overall, it is illustrated based on the PCA response that the elements with influence on treatments are iron, magnesium, sulfur, and sodium.

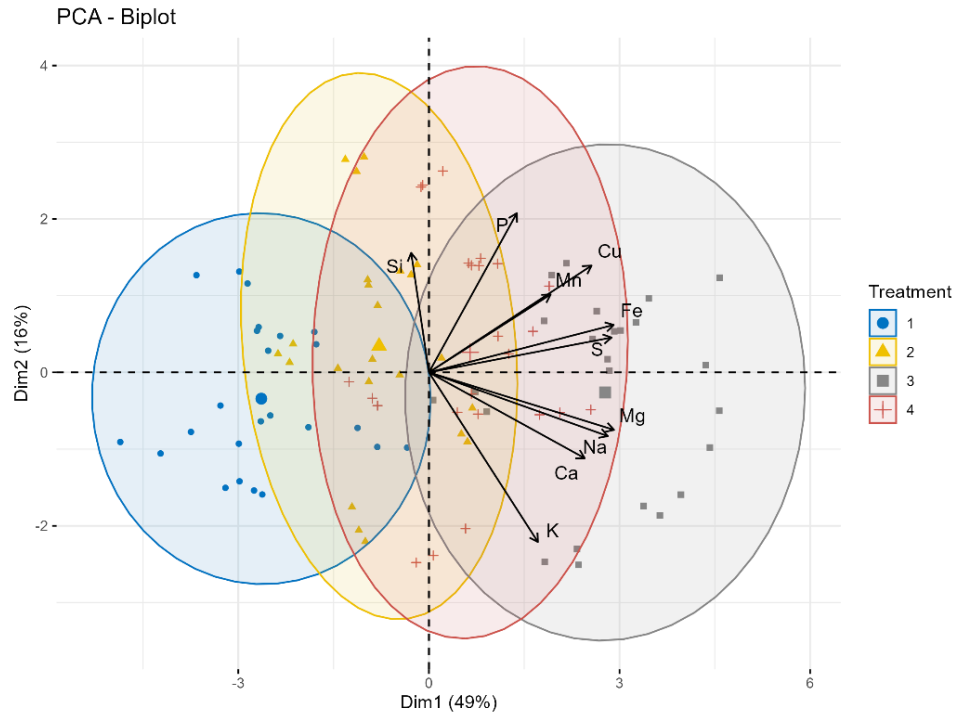


Figure 33: The illustrating of PCA - principal component analysis biplot for the relationship of treatments on macro/micro element concentration under moderate drought conditions (2024). Dim1= 49 %, Dim2 = 16 %, making a total variability of 65 %. Treatments. 1=control, 2=Silicon, 3=Sulfur, 4=Si+S foliar treatments.

The PCA - Principal Component Analysis for spring oat grain elemental concentration under three cultivation seasons: serious, mild, and moderate drought conditions it is show in Figure 34, where a strong independent stability of the year and multi nutritional relation to foliar application. Dim1 explain 40.4% with significant contribution of total variance by iron, copper, magnesium, and sulfur, where a foliar application it is represented in all cultivation seasons. Furthermore, Dim2 accounts of 20.7% in total variance with highly influence of potassium and sulfur distinguished parts. The three year PCA with the Dim1 and Dim2 total contribution by 61.1% of the total variance shows that the foliar application in the accumulation of the elements in spring oat grains is changed due to cultivation seasons.

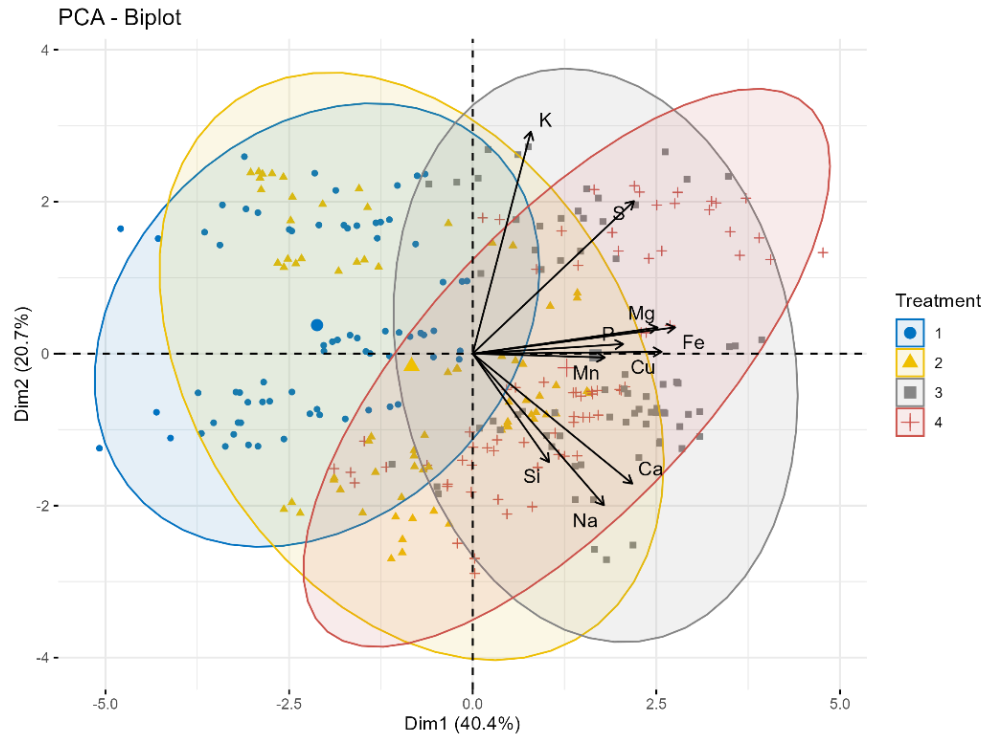


Figure 34: The illustrating of PCA - principal component analysis biplot for the relationship of treatments on macro/micro element concentration under series, moderate and mild drought conditions (2022-2024). Dim1= 40.4 %, Dim2 = 20.7 %, making a total variability of 61.1 %. Treatments. 1=control, 2=Silicon, 3=Sulfur, 4=Si+S foliar treatments.

The results from our experimental and from the previous scientific article are distinguished by the influence of silicon on the nutrient grain content, which shows a difference based on the drought conditions, varieties, nutrient method, and application phase. From our experimental findings, clearly the foliar application of silicon and sulfur is influenced by drought and genotype variation more than universal positive or negative effects. In accordance with Epstein (1999) statement, the silicon application is not uniform in all crops and it is highly dependent on the other elements availability.

5. CONCLUSIONS, SUGGESTIONS

The three-year field experiment (2022-2024) provided a comprehensive effect on the evaluation of foliar treatment of silicon and sulfur on the morphological, physiological and grain mineral quality performance of the spring oat varieties under contrasting environmental seasons.

Across all measured parameters (leaf area index, normalized difference vegetative index, thousands grain weight, yield, transpiration, total conductance assimilation, macroelement and microelement concentrations), environmental variability, specifically the drought intensity, resulted in the strongest influence on all the parameters. Serious drought conditions significantly resulted in lower canopy development and even altered the mineral grain quality in spring oats. Climatic factors, temperature, and water availability represent a dominant parameter on the response of morphological, physiological, and quality responses in spring oats.

In a severely drought-stricken year, spring oat stands reached their maximum Leaf Area Index (LAI) value and Normalized Difference Vegetation Index (NDVI) value as early as the BBCH30 (beginning of stem elongation) growth stage, and by the BBCH83 (early dough) stage, a significant decline was already observed. Under more favorable water conditions, the highest LAI and NDVI value was measured at the BBCH73 (early milk) stage, and it did not or just slightly decline even by the BBCH83 stage. The effect of the treatments on the leaf area index was not significant during the growing season; however, in serious drought (2022), the significantly lowest LAI value at BBCH83 was observed in the Si+S treatment, while the highest was in the control treatment. For the NDVI, differences among treatments were not consistently significant; however, slightly higher values were generally recorded in the Control and Si treatments than in the S or Si+S treatments. Under drought conditions in 2022, the Si+S treatment resulted in the significantly lowest NDVI values at BBCH 83. During both the severe drought of 2022 and the moderate drought of 2024, significantly higher NDVI values at BBCH 83 were observed in the four genotypes originating from Martonvásár compared with the other four genotypes from Szeged (GK) and the Research Institute of Nyíregyháza, whereas under favorable water supply conditions (2023) these differences were not detectable.

Based on the results of the field photosynthesis measurements, the effects of the treatments were most pronounced in the severely drought-affected growing season. The values of the assimilation rate, transpiration, and total conductance measured in 2022, particularly during the second half of the growing season at the BBCH 77 developmental stage, were substantially lower than those recorded in the better-water-supplied years of 2023 and 2024. For all three parameters, the Si+S treatment produced significantly the highest values at BBCH 51, whereas at BBCH 77 the highest values were measured in plants receiving the sulfur treatment. Among the genotypes, under drought conditions at BBCH 77, the cultivar Mv Ménes exhibited significantly the highest values, proving excellent adaptability to drought.

The investigated Si and S treatments did not affect the thousand grain weight in any of the growing seasons; however, a more pronounced reduction in kernel size was observed in the severely drought-affected year. Genetic differences among the cultivars were evident in all three growing seasons, although statistically significant differences were detected only in 2022. The thousand-kernel weight of the cultivars Lota and Mv Pehely was significantly greater than that of the other cultivars examined.

The spring oat grain yield is strongly dependent on the foliar application, drought conditions, and the genotype variation. Across the experimental drought conditions, sulfur contributed to the improvement of the grain yield. The combined application of silicon and sulfur resulted in a positive effect, although it was lower compared to the sole sulfur application. However, a sole silicon application resulted in a limited or negative impact on the grain yield improvement across the cultivation seasons.

A sole or combined foliar application of silicon and sulfur in some scenarios improved grain macro/micro element content of spring oats, but the amount of the improvement depends on the drought conditions and varietal differences. A sole sulfur foliar application or a combination with silicon showed significant differences in the influence of grain mineral content increase. The best foliar performance was the sole application of sulfur by increasing the potassium, phosphorus, sulfur, calcium, sodium, iron, manganese, copper content, except the sodium content, which resulted negatively under serious drought conditions. However, the sole silicon foliar treatments resulted in lower or almost negative impact on the macro

and micro element content in spring oats. From our findings it is recommended that under serious drought conditions, the effect of silicon foliar application has a great on crop stress mitigation and less on the improvement of elemental content.

The genetic variation has a high importance in the grain nutrient content, showing that the varietal divergences have a strong interaction with drought conditions and silicon and sulfur foliar application in spring oats. Even though the experiment is set up in the same soil condition, during three different drought conditions multiple soil types and drought conditions, and more tested varieties are important for the statement of the impact of foliar application on macro/micro element composition in spring oat grains.

6. NEW SCIENTIFIC RESULTS

1. Severe drought (PaDI=11.6 °C 100 mm⁻¹) substantially altered the temporal dynamics of spring oat canopy development, causing an earlier peak (BBCH73) and accelerated decline (BBCH83) of LAI and NDVI compared to mild and moderate drought (PaDI=4.3-6.5 °C 100 mm⁻¹; BBCH73) conditions.
2. Combined foliar applications of silicon and sulfur in spring oats resulted in significantly lower LAI (Si+S: 3.26 m² m⁻²; control: 3.91 m² m⁻²) and NDVI (Si+S: 0.46; control: 0.52) values at the BBCH 83 phenological stage during severely drought-affected growing season. Under more favorable water supply conditions, the effects of the treatments were not statistically significant.
3. Under severe drought conditions, Si, S and Si+S treatments significantly enhanced the photosynthetic performance of spring oat. The effects of foliar-applied silicon and sulfur on the assimilation rate, transpiration and stomatal conductance were strongly dependent on the developmental stage. The combined Si+S treatment was most effective at the early reproductive stage (BBCH51), whereas sulfur alone provided the greatest benefits during grain filling (BBCH77). Sole Si application also improved photosynthetic parameters relative to the control, although its effect was significantly weaker than those of the S and Si+S treatments.
4. Si and S treatments did not affect thousand grain weight in any of the growing seasons. Genetic differences among the cultivars were observed in all three years; however, statistically significant differences were detected only under the severe drought conditions of 2022. The thousand grain weight of the cultivars Lota (28.9 g) and Mv Pehely (27.4 g) was significantly higher than that of the other cultivars evaluated (23.1-25.3 g).
5. Sulfur foliar fertilization consistently improved spring oat grain yield under varying drought intensities, with the strongest response (+22.9%) observed under severe drought conditions, and the lowest (+3.2%) under mild drought, whereas silicon applied alone showed limited effectiveness.

6. Under relatively favorable water supply conditions, foliar sulfur application significantly increased the concentration of all measured elements, with the strongest response observed for Cu (+47.4% compared with the control) and the weakest for Mg (+8.5%). Silicon application alone had limited or even negative effects, particularly under severe drought conditions, where it reduced K (-6.4%), S (-2.4%), and Ca (-13%) concentrations despite increasing Si accumulation in the grain. Under drought stress, the combined Si+S treatment significantly enhanced both macro- and micronutrient concentrations in the grain, with the strongest effects observed for Mg (+9.57%) and Si (+43.2%) relative to the control.
7. The cultivar Mv Pehely exhibited the highest overall grain nutrient accumulation across the growing seasons (2022–2024), particularly for sulfur (S) and magnesium (Mg). In contrast, the genotype GK Kormorán exhibited the highest and most consistent iron (Fe) accumulation across all seasons. The cultivars GK Pillangó and Mv Szellő consistently showed lower grain nutrient concentrations.

7. PRACTICAL UTILIZATION OF RESULTS

1. In spring oat, sulfur and combined silicon + sulfur applications during the growing season (three leaves unfolded-BBCH13, flag leaf stage-BBCH39, early milk stage-BBCH73) exert positive effects on both yield quantity and quality.
2. The sulfur foliar treatment can increase the yield from 3.2% up to 22.9% depending on the environmental conditions.
3. Selecting the best genotypes for the yield performance is an important application for the climate adaptive spring oat management production. On chernozem soil in the Hajdúság region, averaged across the experimental years, the cultivars Mv Ménes, Mv Szellő, Lota, and Panna achieved yield levels exceeding the overall varietal mean.
4. The cultivar Panna recorded the highest yield under severe drought conditions (2022), exceeding that of the lowest-performing cultivar, GK Kormorán, by 54.6%. Mv Ménes showed the best performance during mild (2023) and moderate (2024) drought seasons, with yields 45.9% and 29.6% higher than GK Kormorán.
5. The sole sulfur application can be used in the increase of nutritional value of spring oat, specifically for the increase of potassium, phosphorus, sulfur, calcium, sodium, iron, manganese, and copper grain content, while silicon and sulfur combined application, it can be used for the increase of magnesium and silicon grain content.
6. In the production of high-quality spring oat, the selection of an appropriate genotype is of decisive importance. Based on our investigations, the cultivars Mv Pehely and GK Kormorán exhibited superior grain quality, whereas GK Pillangó and Mv Szellő showed lower macro- and micronutrient contents during the studied period (2022–2024).

8. SUMMARY

This study is established as a field experiment during (2022-2024) cultivation years by providing an evaluation of the silicon and sulfur foliar treatments, drought conditions and genetic variation on the physiological, yield and grain quality content of spring oats (*Avena sativa* L). The study is designed to show the effect drought, foliar and varieties in the crop performance, specifically drought it is an important factor due to the climate change impact on spring oat production.

The field experiment was conducted at the experimental are of the Debrecen University, Hungary, on a haplic chernozem soil. The experimental years resulted on different climatic conditions, including serious drought (2022), mild drought (2023) and moderate drought (2024), classified based on the Pálfi Drought Index – PADI. The various environmental conditions provided a great challenge to evaluate the foliar application of sulfur and silicon under different drought conditions.

The experiment is designed to test eight Hungarian spring oat varieties, four foliar treatments (control, silicon - Si, sulfur - S and Si+S), and three replication cultivated in randomized block design. The measured data included the Leaf area index -LAI, normalized difference vegetative index – NDVI, transpiration, total conductance, assimilation rate, thousands grain weight – TGW, grain yield, and macro/micro element content. The statistics was performed for ANOVA, Pearson correlation, and principal component analysis to estimate the effects of foliar treatments, genotype performance, drought cultivation seasons.

Across cultivation seasons, drought conditions was the most important factor affecting the crop quality and production. Serious drought conditions during the 2022 season, significantly affected the physiological parameters, and yield production. The serious drought stress interfered even in the macro/micro element content in spring oats grain. In contrast, the cultivation season of 2023, influenced the physiological performance, yield, and grain quality.

Foliar application of sulfur, significantly mitigate some of the negative effects of drought stress and influenced the spring oat production and quality. Sulfur treatment significantly increased the grain yield across all cultivation seasons. Furthermore, in grain mineral content the sole sulfur treatments resulted in improvement of macro and micro element content including potassium, phosphorus, sulfur, calcium, sodium, iron, manganese, and copper. These findings suggest that sole sulfur application improves the productivity and the nutritional grain quality of spring oats grain.

The sole silicon application showed limited or negative effects on yield and grain mineral content. However, silicon showed an important effect in stress reduction, specifically under serious drought stresses. The combined foliar application of silicon and sulfur had intermediate effects on yield and grain nutritional content, specifically for magnesium and silicon content.

Genetic divergences was another important factor on spring oat production and quality. Among the tested varieties significant differences resulted due to drought conditions and foliar treatments. Panna variety resulted in the highest yield production under serious drought conditions. Meanwhile, Mv Ménes resulted in highest yield under mild and moderate drought seasons. In the aspect of grain nutritional content the Mv Pehely variety showed the highest sulfur and magnesium content, while GK Kormorán showed the great iron content across all cultivation seasons.

Overall, the results of our study showed that drought stress is an important factor on reducing the spring oat production by affecting the yield and grain nutritional quality. However, a proper sulfur foliar application can mitigate the negative impacts and improve the yield and nutritional content. Furthermore, the genotype selection has a crucial role on the high yield production and favorable nutrient content to ensure better production under different environmental conditions.

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11.LIST OF PUBLICATIONS



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3. Kutasy, E., Csajbók, J., Virág, I. C., Forgács, F., **Bytyqi, B.**: Response of spring oat varieties to silicon and sulphur fertilization in heavy drought.
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In: Smart and Resilient Agriculture - Safety for Future Generations: 61st Croatian and 21st International Symposium on Agriculture: Proceedings. Ed.: Željka Klir Šalavardić, Marin Kovačić, Faculty of Agrobiotechnical Sciences Osijek, University Josip Juraj Strossmayer in Osijek, Bol, Croatia, 58-62, 2026.
8. **Bytyqi, B.**, Kutasy, E.: Physiormorphology responses of spring oat varieties in Silicon and Sulphur application to alleviate drought stress.
In: XI. Interdiszciplináris Doktorandusz Konferencia 2022 = 11th Interdisciplinary Doctoral Conference 2022 : Tanulmánykötet = Conference Book. Szerk.: Kajos Luca Fanni, Bali Cintia, Puskás Tamás, Szabó Rebeka, Pécsi Tudományegyetem Doktorandusz Önkormányzat, Pécs, 80-87, 2023. ISBN: 9789636260705

Foreign language abstracts (1)

9. **Bytyqi, B.**: Physiormorphology responses of spring oat varieties in Silicon and Sulphur application to alleviate drought stress.
In: XI. Interdiszciplináris Doktorandusz Konferencia 2022. november 25-26 = 11th Interdisciplinary Doctoral Conference 25-26th of November 2022 : absztraktkötet = Book of Abstracts. Szerk.: Kajos Luca Fanni, Bali Cintia, Puskás Tamás, Horváth-Polgár Petra Ibolya, Glázer-Kniesz Adrienn, Tislér Ádám, Kovács Eszter, Pécsi Tudományegyetem Doktorandusz Önkormányzat, Pécs, 18, 2022. ISBN: 9789636260699





List of other publications

Foreign language scientific articles in Hungarian journals (1)

10. Melash, A. A., Vad, A., **Bytyqi, B.**, Ábrahám, É. B.: Harnessing diversity in durum wheat (*Triticum turgidum* L.) to enhance climate resilience and micronutrient concentration through genetic and agronomic biofortification.
Agrártud. közl. 2022 (2), 9-20, 2022. ISSN: 1587-1282.
DOI: <http://dx.doi.org/DOI: 10.34101/ACTAAGRAR/2/11053>

Foreign language scientific articles in international journals (2)

11. Melash, A. A., **Bytyqi, B.**, Nyandi, M. S., Vad, A., Ábrahám, É. B.: Chlorophyll Meter: A precision agricultural decision-making tool for nutrient supply in durum wheat (*Triticum turgidum* L.) cultivation under drought conditions.
Life (Basel). 13 (3), 1-20, 2023. EISSN: 2075-1729.
DOI: <http://dx.doi.org/10.3390/life13030824>
IF: 3.2
12. Melash, A. A., Bogale, A. A., **Bytyqi, B.**, Nyandi, M. S., Ábrahám, É. B.: Nutrient management: has a panacea to improve the caryopsis quality and yield potential of durum wheat (*Triticum turgidum* L.) under the changing climatic conditions.
Front. Plant Sci. 14, 1-22, 2023. EISSN: 1664-462X.
DOI: <http://dx.doi.org/10.3389/fpls.2023.1232675>
IF: 4.1

Total IF of journals (all publications): 16

Total IF of journals (publications related to the dissertation): 8,7

The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

25 June, 2026



12. DECLARATIONS

STATEMENT

I wrote this thesis in the framework of the University of Debrecen Kálmán Kerpely Doctoral School for the purpose of obtaining a doctoral degree (Ph.D.) at the University of Debrecen.

Debrecen, 25 June 2026

.....
signature of the candidate
Bekir Bytyqi

STATEMENT

I hereby certify that the doctoral candidate Bekir Bytyqi has carried out his work under my/our supervision within the framework of the above-mentioned Doctoral School between 2020-2024. The candidate has made a decisive contribution to the results of the thesis through his/her independent creative work, and the thesis is the candidate's independent work. I recommend that the thesis be accepted.

Debrecen, 25 June 2026

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signature of the supervisor
Dr. Erika Tünde Kutasy